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SILVATICA
&
LIGNARIA
HUNGARICA

AN INTERNATIONAL JOURNAL
IN FOREST, WOOD
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Szerzői útmutató

The Effect of Soil Moisture on the Reflectance Spectra Correlations in Beech and Sessile Oak Foliage

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Abstract – Reflectance intensities of foliage are mostly due to biomaterials synthesised by plants. Adaptation to the continuously changing environment requires the regulated alteration of metabolic processes, which also influences the UV-VIS (Ultraviolet-Visible) and IR (Infra Red) spectra of leaves. For the calculation of various Vegetation Indices (VIs), e.g. NDVI (Normalized Difference Vegetation Index), the common practice is to use the reflectance spectrum of the whole foliage and when individual leaves of the same plant are sampled, an average VI is derived. On the contrary, our method exploits the small differences between individual leaves of the same plant, making use of the similar distributions of measured reflectance values. Using particular wavelength pairs, linear regressions of reflectance intensities have been investigated. The parameters of these regressions (slope and intercept) have been compared to the temporal variations of the environmental factors, such as temperature, vapour pressure deficit and soil moisture. By assessing the *sensitivity* of the regression coefficient (slope) to the changing environment, wavelength pairs can be selected whose *sensitivity* change reflects the effect of soil moisture deficit on the plant. Based on the state-dependent correlations of the reflectance spectra of plant foliage, a new concept is presented that is capable of indicating the level of environmental stress, e.g. drought stress.

drought stress / state-dependent correlation / UV-VIS and IR spectrometry

Kivonat – Talajnedvesség hatása bükk és kocsánytalan tölgy lombozat reflexiós spektrumainak korrelációira. A lombozat reflexiós intenzitásainak változását elsősorban a növény által előállított anyagok okozzák. A folyamatosan változó környezethez való alkalmazkodás megköveteli az anyagcsere-folyamatok szabályozott megváltoztatását, ami befolyásolja a levelek reflexiós spektrumát is az UV, látható és közeli infravörös tartományban. Különböző Vegetációs Indexek (VI) számításánál, mint pl. NDVI (Normalized Difference Vegetation Index), az általános gyakorlat szerint a teljes lombozat reflexiós spektrumát használják, vagy ha ugyanazon növény különböző leveleit mintázták, akkor egy átlagos VI-t származtatnak. Ezzel szemben módszerünk éppen a növény egyes levelei közötti kis különbségeket hasznosítja, kihasználva a mért reflexiós értékek hasonló eloszlását. Bizonyos hullámhosszpárokat kiválasztva, a mért reflexiós intenzitások lineáris regresszióit vizsgáltuk. A regressziós paramétereket (meredekség és tengelymetszet) összehasonlítottuk a környezeti hatások időbeli változásával, mint pl. hőmérséklet, légköri telítési hiány és talajnedvesség. A regressziós paraméter (meredekség) *érzékenysége*nek vizsgálatával olyan hullámhosszpárokat lehet

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kiválasztani, melyek *érzékenység* változása tükrözi a talajnedvesség hiány növényre kifejtett hatását. Bemutatjuk az új módszer alkalmazhatóságát, amely a növényi lombzat reflexiós spektrumainak állapotfüggő korrelációján alapul, és amely képes a környezeti stressz, pl. szárazságstressz kimutatására.

szárazságstressz / állapotfüggő korreláció / UV-VIS és IR spektrometria

1 INTRODUCTION

Water is not only the media for metabolism, but also one of the key substrates in the cells. The effect of its deficit on various plant tissues and on the whole plant is one of the most studied phenomena in plant science. Recent publications about plant drought stress focused on the genetic background of drought resistance, the modifications of plant hormone systems and enzyme activities, the changing accumulation of biomaterials and the improvement of drought tolerance, among others. The test plants were usually various agricultural crops e.g. wheat, rice, soybeans, grapes and tomatoes. On the contrary, publications studying the effect of drought on trees, particularly by spectrometric methods, are less frequent (e.g. Filella – Peñuelas 1994, Peñuelas et al. 1997a,b, Pu et al. 2003).

The water status of trees can be measured by various methods, e.g. by leaf sampling and a pressure bomb (Scholander et al. 1965), stem psychrometer (Dixon – Tyree 1984) or the recently developed leaf patch clamp (Zimmermann et al. 2008). These methods are able to describe the instantaneous turgor pressure but reveal less about the long term effects of the drought stress, and may be very sensitive to the sampling time and conditions. On the other hand, the overall effect of the unfavourable conditions may be estimated by analysing the bio-production of the plant, e.g. yield, growth or accumulated dry material, but it demands a longer period or a full growing season in order to obtain significant differences.

The measurement of the leaf reflectance spectrum is a very promising way to characterize drought stress, and many different methods have been proposed to interpret the reflectance data. Many “high spectral resolution reflectance vegetation indices” have been developed to monitor biomass, phenology or physiology (Peñuelas – Filella 1998). These methods usually measure the reflectance at a few selected wavelengths and calculate a Vegetation Index (VI) from these reflectance values.

For example, a Simple Ratio (SR) can be used to estimate green biomass: $SR = R_{NIR} / R_{red}$, where R is reflectance and NIR stands for near infrared (Jordan 1969). A more robust and widespread method is the Normalized Difference Vegetation Index (NDVI) which is calculated as: $NDVI = (R_{NIR} - R_{red}) / (R_{NIR} + R_{red})$ and used not only at ground level but also by airborne or satellite remote sensing (Rouse et al. 1973). NDVI is mainly sensitive to the green biomass (Gamon et al. 1995), but decent correlations are found with many other environmental or physiological variables. The exact wavelengths of SR and NDVI are somewhat arbitrary, and vary according to the spectral sensitivity of the sensor that is used or the goal of the investigation. Many practical uses of the NDVI have already been proposed and also used in industry, e.g. irrigation scheduling (e.g. Hunsaker et al. 2007, Aldakheel 2011), soil salinity management (e.g. Li et al. 2014), yield prediction (e.g. Teal et al. 2006, Moriondo et al. 2007) or fertilizer dosage adjustment (e.g. Stone et al. 1996, Crain et al. 2012).

Not only red and near infrared light, but many other wavelengths have been investigated, and various other VIs have been proposed for different purposes. *Table 1* summarises the most frequently used VIs along with the wavelengths they use. Many studies have been conducted to compare different VIs for specific application purposes, e.g. stress detection (e.g. Zarco-Tejada et al. 2004, Eitel et al. 2007, Pu 2008).

Table 1. The most frequently used Vegetation Indices along with their used wavelengths.

Vegetation Index (VI)	Abbrev.	Wavelengths	Reference
Simple Ratio	SR	NIR, red	Jordan (1969)
Normalized Difference Vegetation Index	NDVI	NIR, red	Rouse et al. (1973)
Normalized Difference Pigment Index	NDPI	430, 680	Baret et al. (1988)
Modified Chlorophyll Absorption in Reflectance Index	MCARI	550, 670, 700 or 550, 670, 800	Daughtry et al. (2000) or Haboudane et al. (2004)
Transformed CARI	TCARI	550, 670, 700	Haboudane et al. (2002)
Triangular Vegetation Index	TVI	550, 670, 750	Broge - Leblanc (2001)
Modified Triangular Vegetation Index	MTVI	550, 670, 800	Haboudane et al. (2004)
Renormalized Difference Vegetation I.	RDVI	670, 800	Roujean - Breon, (1995)
Soil Adjusted Vegetation Index	SAVI	670, 800	Huete (1988)
Improved SAVI with self-adjustment f.	MSAVI	670, 800	Qi et al. (1994)
Optimized Soil-Adjusted Vegetation I.	OSAVI	670, 800	Rondeaux et al. (1996)
Greenness Index	G	554, 677	-
Zarco-Tejada & Miller Index	ZMI	710, 750	Zarco-Tejada et al. (2001)
Simple Ratio Pigment Index	SRPI	430, 680	Peñuelas et al. (1995)
Normalized Phaeophytinization Index	NPQI	415, 435	Barnes et al. (1992)
3-band ratio	RATIO	975, 1200, 1750	Pu et al (2003)
Photochemical Reflectance Index	PRI	531, 570 or 528, 567	Gamon et al. (1992)
Normalized Pigment Chlorophyll Index	NPCI	430, 680	Peñuelas et al. (1994)
Carter ratios	Ctr	420, 695 or 605, 760 695, 760 or 710, 760	Carter (1994)
Lichtenthaler indices	Lic	450, 800 or 440, 690	Lichtenthaler (1996)
Structure-Independent Pigment Index	SIPI	445, 680, 800	Peñuelas et al. (1995)
Vogelmann indices	Vog	740, 720 or 715, 726, 734, 747 or 715, 720, 734, 747	Vogelmann et al. (1993)
Gitelson and Merzlyak	GM	550, 750 or 700, 750	Gitelson - Merzlyak (1997)
Water Index	WI	900, 970	Peñuelas et al. (1997b)
Normalized Difference Water Index	NDWI	860, 1240	Gao (1996)
Disease Water Stress Index	DSWI	547, 802, 682, 1657	Galvão et al (2005)

Not only indices can be calculated from individual reflectance values, but other properties of the spectra may also be analysed. The “Red Edge” method calculates the derivative of the reflectance spectra in the red - near infrared region, and seeks the wavelength of maximum slope. The Red Edge position and shape can be an indicator of the chlorophyll content of a plant and its water status, among others (e.g. Filella – Peñuelas 1994). Pu et al. (2003) assessed the water status of *Quercus agrifolia* leaves using different absorption characteristics, such as wavelength position, absorption depth and width, and also a 3-band ratio at 795, 1200 and 1750 nm.

A recent study by Tan et al. (2013) compared 54 different VIs to find the best predictor for the Fraction of Photosynthetically Active Radiation (FPAR) and found that not a single VI but a combination of two VIs showed the best results. The Index Database maintained by Henrich et al. (2012) currently (in 2015) registers 517 different indices used by remote sensing. Thirty three of them aim to assess the water content of vegetation and 10 are related to stress. Clearly, there is a lot of information buried in the reflectance spectra of leaves.

The method proposed by us offers a new approach to measure not only the short term, but also the cumulative effect of environmental stress with a potentially non-destructive method using the reflectance spectra of the leaves. It is based on the concept of the state-dependent correlation between biochemical variables by Németh et al. (2009a). If more leaves are sampled from the same plant for a VI measurement, the results of the individual leaves are not the same; therefore they are usually averaged to yield a single VI for the whole plant. On the contrary, our method exploits these small differences: the distribution of the measured reflectance values and the correlations between them.

2 THEORETICAL BACKGROUND AND RELATED WORK

Plants tend to adjust their physiological state to the actual conditions of their environment. The primary environmental factor is light intensity, which is different in the foliage from leaf to leaf; therefore the intensities of photosynthesis are different in the individual leaves. Thus, the concentrations of plant metabolites have a distribution pattern within the foliage. Environmental factors are able to modify the expected values and standard deviations of these metabolite distributions, and they can also distort the shape of these distributions. Thus, the effect of environmental conditions on foliage appears in the distribution functions of the metabolites. This means that the expected values and the standard deviations of the metabolites can change with alterations of environmental conditions; the distribution functions of the metabolites can move to and fro along their scales (Badácz et al. 2011; Németh 2013).

If there are at least two metabolites in the metabolism whose amounts are regulated synchronously, then their types of distributions are necessarily the same, and the levels of metabolites correlate linearly to each other (Németh et al. 2009a). The theoretical equation of state-dependent correlation is deduced from the identity of the distributions of standardized metabolite levels, and this theoretical linear relationship can be approximated by regression analysis. The correlating metabolite concentrations provide a regression straight line. The slope and the intercept of this straight line are able to reflect alterations in the moments (expected value, standard deviation) of metabolite distributions induced by the environmental factors. Thus, the state-dependent regressions can indicate the modifications in environmental condition.

2.1 State-dependent regressions of the reflectance spectra

The reflectance spectrum, which is perceived as various colours in the visible range, pertains to the mixture of the different materials synthesized by leaf cells. Their amounts are the daily products of the photosynthesis that follow periodic alterations controlled by metabolic regulation. The diurnal variation of chlorophylls is one of the well-known cases of metabolic oscillations (e.g. Shimada 1958, Busheva et al. 1991). Similar diurnal changes have also been detected in other pigments, e.g. the xanthophylls (Adams – Demmig-Adams 1992).

Due to their significant light absorption in the visible and infrared regions, plant pigments, e.g. chlorophylls, carotenoids, xanthophylls, etc. are the main materials that dominate the reflection spectrum of the leaves. Since their distributions within the foliage are influenced by some environmental factors, the distributions of characteristic reflection (or absorption) intensities are also sensitive to environmental factors. Moreover, if the type of their distribution is the same, then the reflectance values belonging to various wavelengths will also linearly correlate and provide state-dependent regression straight lines. In conclusion, by measuring the spectra of leaves and deriving their state-dependent regressions, the alterations of the physiological states of the plants can be tracked.

If the synthesis and decomposition of two arbitrary metabolites in the plant cells are regulated synchronistically, the actual concentration values of such metabolites are not independent of each other. Moreover, if their synchronistic regulation has linear character, then their concentrations will also be related to each other in a linear manner. Absorbance values (A) obtained by spectroscopic measurement at particular wavelengths ($A_{\lambda 1}$ and $A_{\lambda 2}$) are proportional to the concentrations of these synchronously regulated metabolites and thus they are also linearly linked.

If the reflectance spectra have two such wavelengths (λ_1 and λ_2), whose absorbance intensities ($A_{\lambda 1}$ and $A_{\lambda 2}$) have the same type of distribution, then the standardised values of those absorbance intensities must be identical:

$$\frac{A_{\lambda 1} - \mu_1}{\sigma_1} = \frac{A_{\lambda 2} - \mu_2}{\sigma_2} \quad (1)$$

Where μ is the expected value and σ is the standard deviation of the A_λ absorbance intensity, measured at λ wavelength. Rearranging Equation 1 produces the theoretical equation for the state-dependent correlation of reflectance spectra:

$$A_{\lambda 1} = \frac{\sigma_1}{\sigma_2} \cdot A_{\lambda 2} + \frac{\sigma_2 \cdot \mu_1 - \sigma_1 \cdot \mu_2}{\sigma_2} \quad (2)$$

We investigated those wavelength pairs, whose absorbance intensities satisfy the equivalence criteria of Equation 2. This equation can be approximated by a linear regression: by fitting a straight line to the corresponding absorbance values:

$$A_{\lambda 1} = m \cdot A_{\lambda 2} + b \quad (3)$$

Where m is the slope and b is the intercept of the regression straight line.

2.2 Sensitivity and response time

On the base of the analogy between technological and biological control systems, the concept of *gain* can also be applied to physiological processes (Németh 2009b). Adaptation to different environmental conditions appears in altering the parameters m and b , which is visible from the different $A_{\lambda 1}$ to $A_{\lambda 2}$ linear regression. The *sensitivity* of the state-dependent regression can be evaluated by comparing the magnitude of the environmental changes e.g. temperature, to the changes of regression parameters m and b . If the relationship is more or less linear, then the slope of this straight line is hereafter called “*sensitivity*” (S). The control theory suggests that plants under stress exhibit greater *sensitivity* to disturbing environmental factors and thus S increases.

In a controlled environment such as a greenhouse, if we abruptly change (as a step function) only one influencing factor, e.g. temperature, we can measure the properties of the response: how intensely and how quickly the plant responds to reach a new quasi-stationer state. This measurement yields the *sensitivity* and the time constant of the system for the selected environmental parameter. However, under natural climatic conditions there are many influencing factors that change simultaneously and gradually. We can measure the response of the metabolic system, but the magnitude and duration of the influencing factor is not evident. To resolve this problem, the time series of the influencing environmental variables are needed with several samples at different times, which show the actual state of the metabolic system.

The response of the plant to the changing environment is relatively slow, so the physiological state of the plant does not closely follow e.g. the daily course of the temperature but responds to a long term trend. This behaviour dampens abrupt changes and provides a more stable biological system dynamics with less fluctuation. This means that the actual state of a plant does not entirely depend on the instantaneous value of the influencing parameter, but is determined by the cumulative effect of a previous period. The length of this influential time interval can be on the order of days, and is called hereafter the “*time of influence*” (t_{infl}).

The length of t_{infl} can also change, depending on environmental factors. To solve this problem, we calculated S as the linear regression of m against the environmental variable with many different t_{infl} to find that time interval which minimizes the variance, and therefore best describes the perceived change (see section 3.5.5).

2.3 The influence of the environment on the sensitivity

If the *sensitivity* (S) changes over time, we can relate its change to the course of other environmental factors. With sufficient correlation and if logic doesn't prove otherwise, we may assume that the influencing factor has been found (or at least one of them). In this paper we demonstrate that soil moisture has a good agreement with *sensitivity* changes at some selected wavelength pairs and thus these wavelengths are suitable for the indication of drought stress.

3 MATERIALS AND METHODS

3.1 Site conditions

Leaf samples were collected at the Magasbérc Artificial Drought Experiment in the Sopron Mountains (N47°39'14", E16°27'34"), Hungary, from two 64-year-old beech trees (*Fagus sylvatica*) and two sessile oak trees (*Quercus petraea*). Slight drought (soil moisture deficit) was simulated at a portion of the area by building a roof of plastic foil on wooden frames 1 m above the ground, which excluded precipitation. The treated area was already separated in 2012 below ground by plastic sheets buried in a 1 m deep trench, to cut far reaching roots and prevent possible horizontal water movement. In addition, the site is located on a hilltop where not much surface or subsurface flow is expected so that the treated trees could be isolated from any water supply.

We collected leaf samples 9 times between 11th of July and 30th of September 2014, with a sampling interval of about 2 weeks. The covering roof was assembled after the third sampling and thus, after that time, the treated area received no precipitation, which resulted in continuously decreasing soil moisture. In contrast the control area received the subsequent rainfalls and its soil moisture recovered after an intense decrease in July, thanks to the rainy and cold weather in August (Figure 1). Except for soil moisture, all the other environmental factors acted equally on the trees.

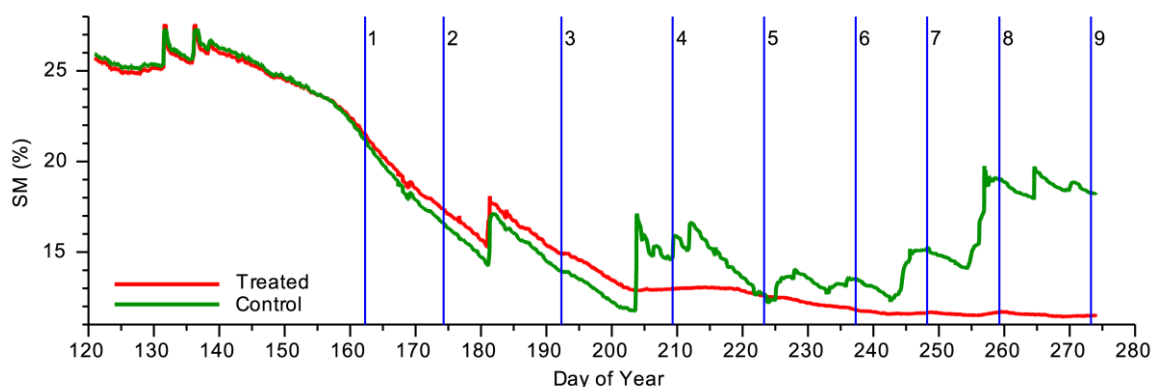


Figure 1. Time series of total soil moisture (SM) at the Treated and the Control plot. Blue vertical lines show the time of sample collection.

3.2 Sampling protocol

We collected the leaf samples in the morning from the upper part of the canopy, using rope technique. We cut a small branch containing at least 7 healthy leaves from 1 treated and 1 control tree of both species, hereafter denoted as TB (Treated Beech), CB (Control Beech), TO (Treated Oak) and CO (Control Oak). The cut branches were placed immediately into water and processing began no more than 1 hour after sample collection. Experience shows that this procedure minimizes the impact of cutting off the branches on the measurement results.

3.3 Environmental data

Meteorological parameters and soil moisture were continuously monitored with a 5 minute data logging interval at the site and a nearby (400 m) micrometeorological tower. Soil moisture was measured by EC-5 sensors (Decagon Devices Inc., USA) close to the sampled trees, buried at 5 depths (10-20-30-50-90 cm). We calculated the total soil moisture (SM) by a weighted mean of the 5 data. Air Temperature (T) and relative humidity was measured by HMP155 sensors (Vaisala, Finland) above the canopy. From this data we calculated Vapour Pressure Deficit (VPD) after Hardy (1998), which is the difference between the actual water vapour pressure and the saturation water vapour pressure at a particular temperature. Unlike relative humidity, Vapour Pressure Deficit has a simple nearly straight-line relationship to the rate of evapotranspiration: as VPD increases the plant needs to draw more water from its roots, therefore it is a good indicator of the evaporative demand.

3.4 Reflectance spectra

We measured the reflectance spectra of the leaves (7 by each tree) in the UV-VIS range of 200-1400 nm and 2 nm resolution with a Shimadzu UV-2600 spectrophotometer, and in the IR range of 700-400 cm^{-1} and 1 cm^{-1} resolution with a Shimadzu IRAffinity-1 spectrophotometer equipped with an HATR-10 total reflection accessory (Shimadzu Corp.). The wavenumber scale (cm^{-1}) of this second instrument was converted to nm scale (2500-14940 nm) to avoid the confusion of scales on the graphs. The reflectance spectra of each leaf was smoothed by a 10 nm wide moving average, and the Standard Normal Variate (SNV) transformation was used to pre-process the data.

3.5 Data evaluation

Data processing and evaluation were done in Scilab 5.4.1 (Scilab Enterprises), and the covariance analysis and grouped linear regression were carried out in StatsDirect.

3.5.1 Selection of wavelength pairs

A sample set of 7 reflectance spectra (collected at the same time from the same tree) is shown in Figure 2 with the marks of the wavelengths demonstrated in this paper.

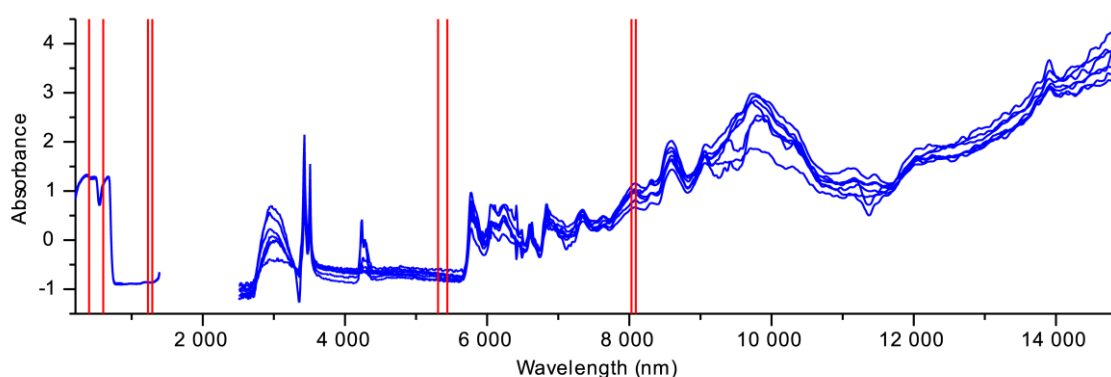


Figure 2. Sample reflectance spectra set of 7 leaves, collected from the Control Beech, at the first sampling. Red vertical lines mark the demonstrated wavelengths.

Using a 10 nm resolution, the combined UV-VIS-IR spectra provide 928,884 possible pair combinations. Of course, many neighbouring wavelengths show the effect of the same material and not all the materials show linear correlation, which we looked for. To find promising wavelength pairs, we calculated the correlation matrix of the spectra, from the 7 leaves sampled at the same time. The Pearson R correlation coefficient shows the strength

and sign of the linear correlation. On these autocorrelation ‘maps’ (Figure 3) those regions have been separated that show remarkable linear correlation. In each region, wavelength pairs have been selected that exhibit the highest average correlation throughout the 9 samples. However there is no guarantee at this point that these pairs carry useful information, as e.g. they may represent two characteristic wavelengths of the same material. During the evaluation process detailed below, the useless pairs were filtered out gradually. In the following sections we demonstrate the workflow using the example of the 400-600 nm wavelength pair.

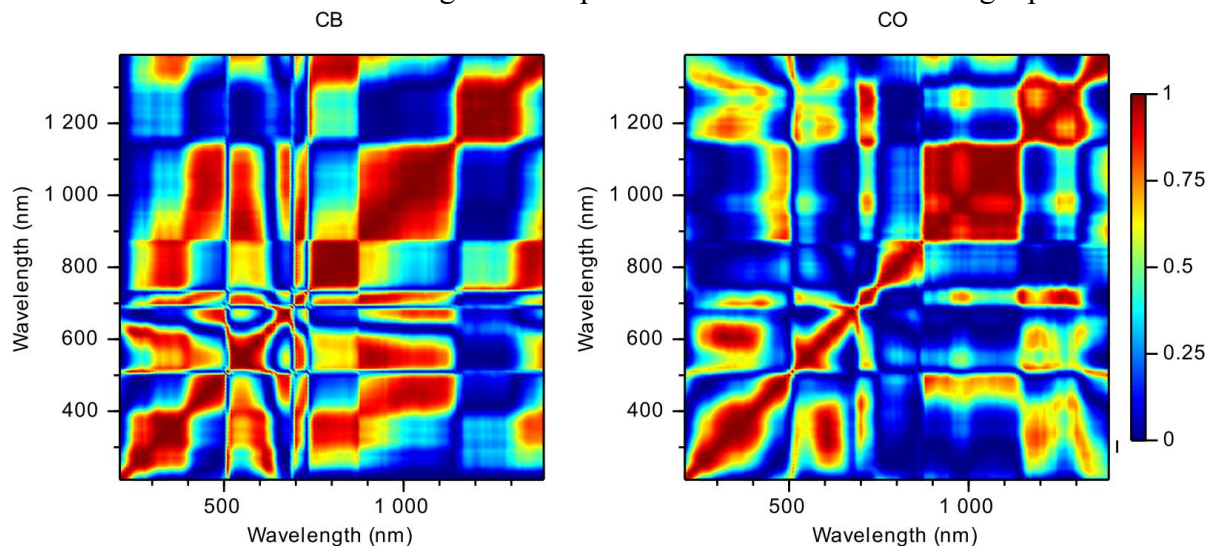


Figure 3. Two examples of autocorrelation ‘maps’ in the 200-1400 nm range, computed from 7 leaves of the first sampling. CB: Control Beech, CO: Control Oak.

The colour shows the squared correlation coefficient (R^2):
more red means stronger linear correlation.

3.5.2 State-dependent regressions

The linear regressions of the absorbance values (Equation 3) of the previously selected wavelength pairs were calculated for all the 9 samplings that produced a slope (m) and an intercept (b) for each sample (Figure 4).

Table 2. Pair wise slope and intercept comparison of the regressions for 400-600 nm absorbance values of the Control Beech at the 9 sampling times. The upper triangle of the table contains the probability limits of significance of slope comparisons; the lower one belongs to the intercept comparison. Darker colours show more significant differences.

		Slope comparison								
Vertical line separation	. P	sample 1	sample 2	sample 3	sample 4	sample 5	sample 6	sample 7	sample 8	sample 9
	sample 1	-	0.5284	0.8538	0.0332*	0.1125	0.8961	0.8779	0.6364	0.7618
	sample 2	0.3650	-	0.7548	0.1246	0.3792	0.6735	0.5839	0.4124	0.8676
	sample 3	0.3156	0.8349	-	0.0841	0.2599	0.8340	0.8041	0.6272	0.9091
	sample 4	0.2279	0.6401	0.7820	-	0.4450	0.1312	0.0642	0.0361*	0.1214
	sample 5	0.0069**	0.0405*	0.0701	0.1574	-	0.3175	0.1954	0.1149	0.3475
	sample 6	0.0269*	0.1017	0.1449	0.2697	0.8116	-	0.9770	0.9064	0.7779
	sample 7	0.0005**	0.0029**	0.0063**	0.0221*	0.3104	0.2481	-	0.8377	0.7357
	sample 8	0.0002**	0.0003**	0.0005**	0.0029**	0.0765	0.0595	0.4210	-	0.5762
	sample 9	<0.0001**	<0.0001**	0.0005**	0.0022**	0.0473*	0.0451*	0.3138	0.8569	-

With ANCOVA (Analysis of Covariance) homogeneity test, those wavelength pairs were rejected that showed no or very little variation in the parameters m and b . The reason is that although they showed a good linear correlation, they were not sensitive to external environmental factors. Table 2 shows an example of the significance levels of a pair wise slope and intercept comparisons. The majority of compared pairs of the regressions are below the significance criteria, therefore these regression pairs can significantly be distinguished by their slopes or their intercepts (or both).

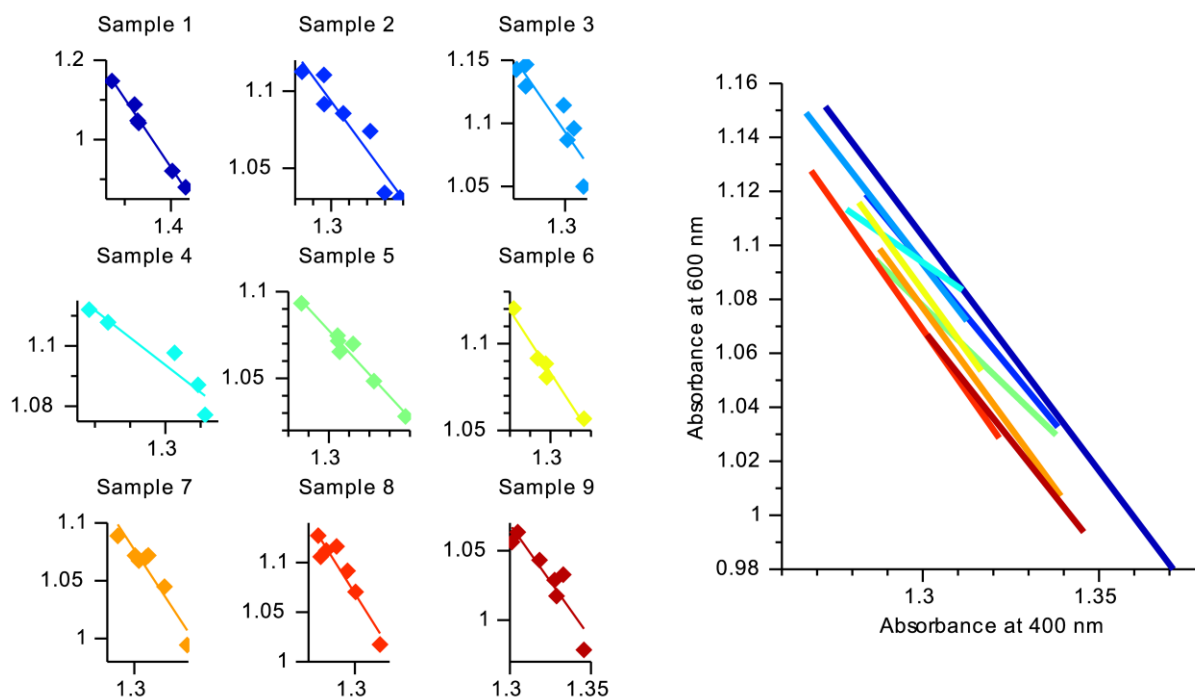


Figure 4. Example of the straight line regressions for 400-600 nm absorbance values of the Control Beech at the 9 sampling times.

3.5.3 Distribution test

The absorbance values of the selected wavelength pairs were standardized with the group means and standard deviations and plotted against each other. Ideally, the scatter plot should have a unity slope and zero intercept ($m = \pm 1$, $b = 0$) and the histograms must show similar distributions (but not necessarily a normal distribution) in order to satisfy the equivalence criteria of Equation 1. Figure 5 demonstrates that initial assumptions are strengthened and thus the state-dependent correlation theory can be applied.

3.5.4 Environmental data processing

It was necessary to characterise the effect of the continuously changing environment during the influencing time intervals (t_{infl}) before each sampling. Therefore, two characteristic values were calculated: the *mean* ($T_{mean}(t_{infl})$, $VPD_{mean}(t_{infl})$), and the average rate of *change*, which is obtained by fitting a straight line to the time series, and used the slope (or derivative) of this line as an indicator of the intensity of the change ($T_{change}(t_{infl})$, $VPD_{change}(t_{infl})$). E.g. $T_{change}(3) = -1.5$ °C/day means, that during the influencing 3 days before sampling, the cooling was an average 1.5 °C per day. But the exact length of the time interval was not previously known and therefore representative values (*mean* and *change*) were calculated for a series of different intervals, e.g. $T_{change}(t)$, where t ranges between 2 to 12 days with 1 hour resolution, which includes every possible value of the parameter t_{infl} .

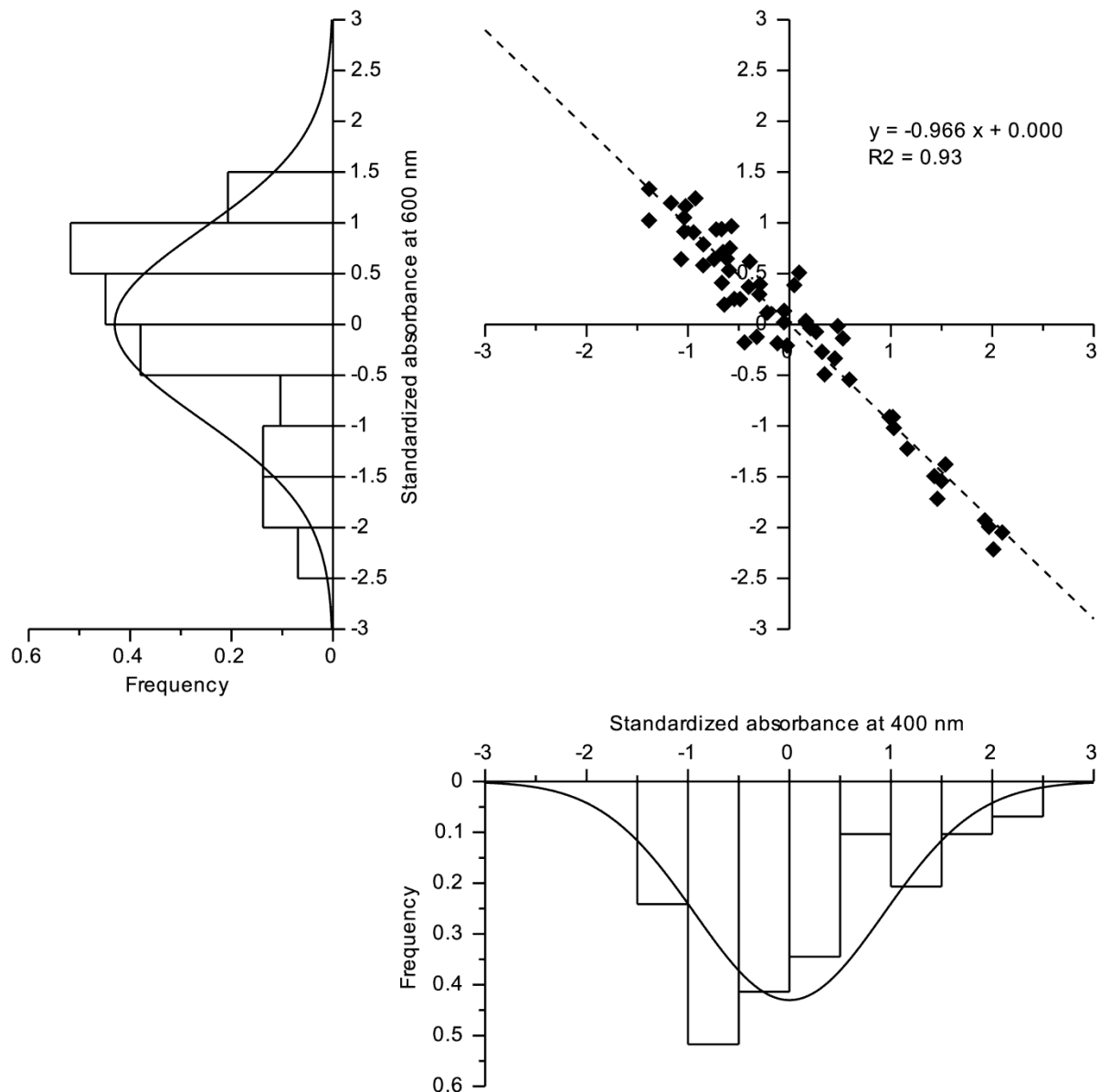


Figure 5. Control Beech 400-600 nm standardized absorbance values and their relative frequency distribution.

3.5.5 Sensitivity (S) and time of influence (t_{infl})

As defined before, the S is the sensitivity of the regression parameters (m and b) to environmental conditions. Assuming constant sensitivity, if the slope m of a state-dependent regression is plotted against the environmental factor e.g. T_{change} , a derived straight line may be obtained. The slope of this straight line is the sensitivity related to temperature change ($S_{Tchange}$). It shows how the state-dependent regression of the selected absorbances changes, when the weather is warming or cooling. If all the slopes of the state-dependent regressions fit to a common line, then the light absorbances at those wavelengths are not sensitive to any additional environmental stress factor, because the sensitivity is stable ($S_{Tchange} = const.$). On the contrary, significant changes of S have been sought that can be used as an indicator of environmental stress. To investigate the possible changes of S as time passes, the samplings were grouped into shorter periods, and the S of each period was computed individually. Since there were only 9 samplings, 6 overlapping periods (P) were created from groups of 4 subsequent samplings, e.g. P_1 : sample 1-2-3-4, P_2 : sample 2-3-4-5, P_3 : sample 3-4-5-6, etc.

The *time of influence* (t_{infl}) is the time interval before the sampling that describes the observed state with the highest probability. To find this time, for each *period* the Pearson R correlation coefficient was calculated for all the cases of m versus e.g. $T_{change}(t)$, where the latter is the characteristic value of the environmental parameter calculated at every possible t_{infl} (2-12 day). Graphically, it is equivalent to fitting a straight line to the measured m vs. $T_{change}(t)$ at all the possible t_{infl} , and R describes the goodness of fit. The change of this correlation coefficient (R) against time (t) is shown in Figure 6.A for all 6 *periods*. The maximum (or minimum) of this curve shows the time of the best fit and thus this time is the t_{infl} . The same concept can also be applied for other environmental variables (e.g. VPD) and both the *mean* and *change* values.

The t_{infl} values calculated for the different *periods* sometimes show good agreement, but many times there are some *periods* out of the 6, which produce extremely low or high values (e.g. 2.6 day in Figure 6.A). In theory the *time of influence* is not a fixed value, but may change as S , since t_{infl} is also a biological response parameter. But these extremes are probably due to a special pattern of the weather alteration that misguides the algorithm. To safely calculate the real t_{infl} for each *period*, more samplings were needed. To avoid the disturbing effect of these outliers, we assumed a constant t_{infl} during all the *periods*. This is based on the mean R of the 6 *periods*: the time of the maximum (or minimum) of this R_{mean} indicates the presumed common t_{infl} (Figure 6.B). Graphically, this t_{infl} ensures the best common fit of the 6 lines. The slopes of these 6 lines are the required *sensitivities* ($S_{Tchange}$); see Figure 6.C.

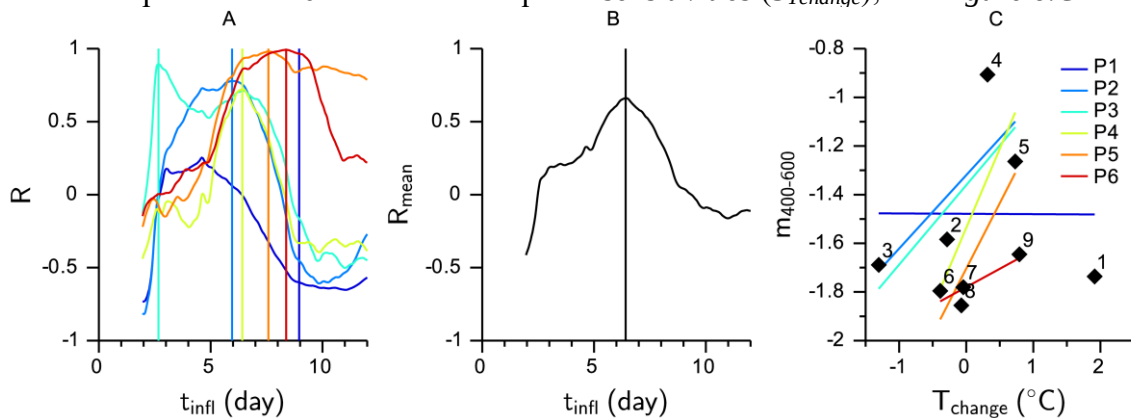


Figure 6. Control Beech 400-600 nm response to T_{change} variations.

A.) The correlation coefficients (R) vs. all possible t_{infl} for the 6 periods (P).

The maximum (or minimum) of each curve indicates the assumed t_{infl} , marked with a vertical line.

B.) The mean of the 6 correlation coefficients (R_{mean}). Its maximum indicates the common t_{infl} .

C.) m vs. $T_{change}(t_{infl})$ with the regression lines of the 6 periods. The slopes of these 6 lines are the sensitivities of the periods ($S_{Tchange}$).

3.5.6 Changing sensitivity in response to environmental stress

We needed to describe the overall effect of environmental conditions which may induce a stress syndrome in the plants. We calculated the mean values of the main environmental variables (SM , T and VPD) during the presumed common t_{infl} before every sampling, and from these ones, the *period means* were computed for the 6 *periods*. In this way, for every *period* 3 environmental factors ($SM_{period-mean}$, $T_{period-mean}$, $VPD_{period-mean}$) and a *sensitivity* (S) were obtained. Plotting S against the *period means* of the environmental factors, characteristic curves are revealed. The first graph in Figure 6 shows that with decreasing soil moisture the *sensitivity* increases (negative slope decreases) which can also be seen in Figure 5.C as more steep lines. Similarly, with increasing soil moisture the *sensitivity* decreases as expected. On the contrary, the *sensitivity* shows no clear connection to the temperature or the vapour pressure deficit (Figure 7. T and VPD).

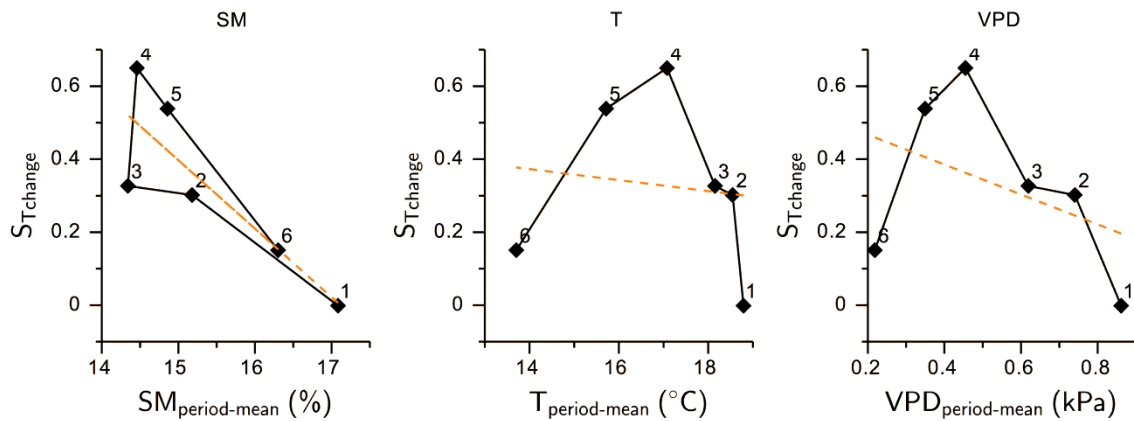


Figure 7. Control Beech 400-600 nm sensitivity for temperature change ($S_{Tchange}$) during the 6 periods (identified by numbers) vs. the environmental variables: SM - Soil moisture, T - Mean temperature, VPD - Vapour Pressure Deficit.

4 RESULTS AND DISCUSSION

Applying the previously described method, wavelength pairs that showed systematic sensitivity changes under drought stress were selected.

There are wavelengths which work well for both species, e.g. 400-600 nm, which is presented in Figure 8. Here, the regression parameter ($m_{400-600}$) varies in response to the average temperature change (T_{change}). The sensitivity of the regression in the 6 periods is expressed by the sensitivity for temperature change ($S_{Tchange}$). This $S_{Tchange}$ is plotted against the average soil moisture ($SM_{period-mean}$), which shows that in beech trees (Figure 8 left) the sensitivity increases with decreasing soil moisture (increasing drought). This means if the trees are under stress, the change of $m_{400-600}$ is bigger for the same amount of temperature change. The sensitivities of control beech (CB) show a nearly linear relationship with the soil moisture. The sensitivities of the treated beech (TB) show less change for a while, but below a certain soil moisture content (< 13%) they increase considerably.

The same seems to be true for the oaks (Figure 8 right); the only difference is the sign of the sensitivity. This negative sign means that for temperature increase (warming), oak trees raise the absolute magnitude of $m_{400-600}$. On the contrary, beech trees lessen the absolute magnitude of $m_{400-600}$ under the same circumstances. What matters is not the sign, but the magnitude of the sensitivity, which increases with the decreasing soil moisture as expected, signalling greater stress. If the wavelengths for the calculation of m are simply exchanged (e.g. not 400-600 nm, but 600-400 nm), the sign of S reverses.

Regressions of wavelength pairs, which can express sensitivity to the VPD_{change} are also be found. An example is shown with the beech trees in Figure 9, measured at 1230-1290 nm.

Not only the visible or near infrared range can be informative, but sensitive wavelengths in the middle infrared region can also be identified. An example for the oak trees at 5310-5440 nm ($1883-1838\text{ cm}^{-1}$), and for the beech trees at 8030-8090 nm ($1245-1236\text{ cm}^{-1}$) is depicted in Figure 10. Both regressions of wavelength pairs are sensitive to the rate of temperature change (T_{change}). These regressions show behaviour similar to the previously detailed examples.

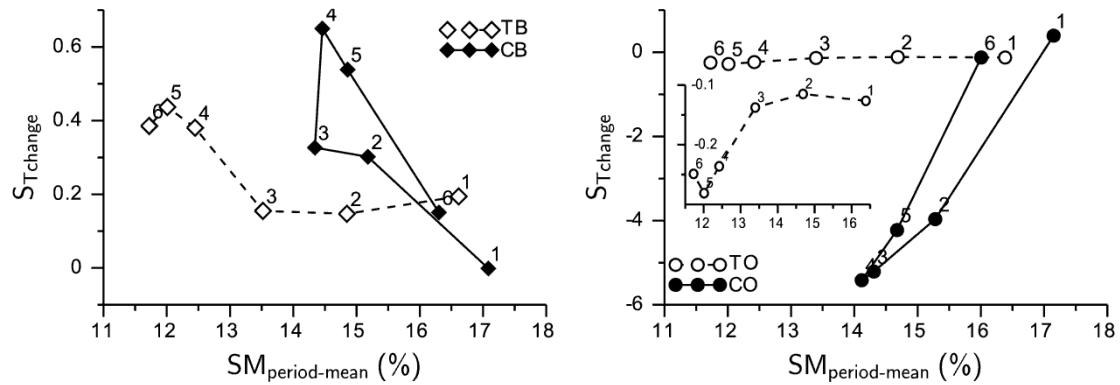


Figure 8. Beech (left) and Oak (right) 400–600 nm sensitivity ($S_{Tchange}$) vs. average Soil Moisture ($SM_{period-average}$) during the 6 periods. $S_{Tchange}$ is the sensitivity of $m_{400-600}$ to T_{change} variations. TB: Treated Beech, CB: Control Beech, TO: Treated Oak, CO: Control Oak.

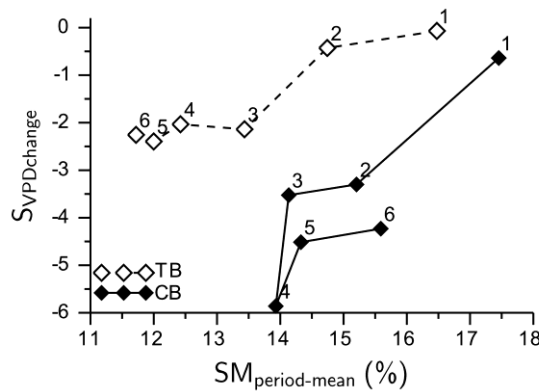


Figure 9. Beech 1230–1290 nm sensitivity ($S_{VPDchange}$) vs. average Soil Moisture ($SM_{period-average}$) during the 6 periods. $S_{VPDchange}$ is the sensitivity of $m_{1230-1290}$ to VPD change variations. CB: Control Beech, TB: Treated Beech.

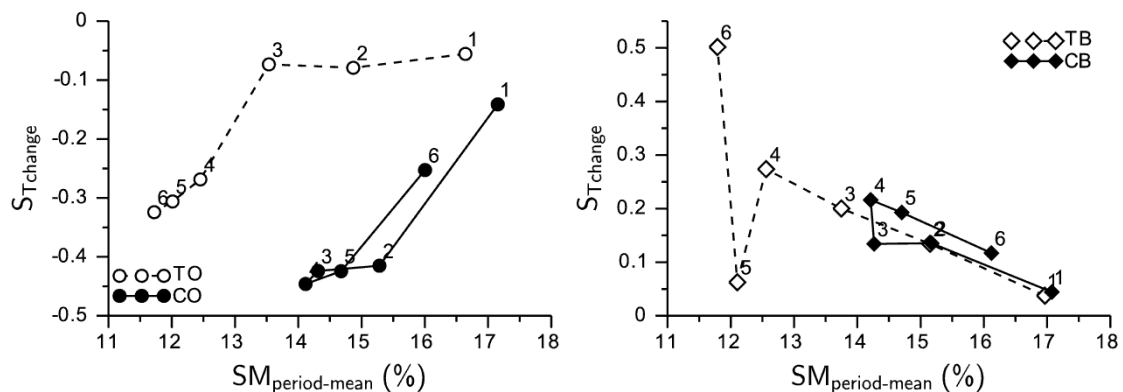


Figure 10. Oak 5310–5440 nm (left) and Beech 8030–8090 nm (right) sensitivity ($S_{Tchange}$) vs. average Soil Moisture ($SM_{period-average}$) during the 6 periods. $S_{Tchange}$ is the sensitivity of $m_{5310-5440}$ and $m_{8030-8090}$ to T_{change} variations, respectively. TO: Treated Oak, CO: Control Oak, TB: Treated Beech, CB: Control Beech.

At 400 nm and 600 nm wavelengths the absorbance intensities are mainly affected by the photosynthetic pigments (chlorophylls, xanthophylls, carotenoids, etc.). At 400 nm almost all of the pigments contribute to the resultant absorption, but at 600 nm the absorbance is determined mainly by chlorophylls. Thus the $m_{400-600}$ slope changes of the state-dependent regressions indicate the variation in the ratio of chlorophylls compared to the total pigment content, and this variation is sensitive to the environmental parameters such as temperature and soil moisture. Between 1200 and 1300 nm, water and the lingo-cellulose system are the significant influencing factors for the light absorption. At even higher wavelengths, the overtones of vibration resonances of the molecules prevail the absorbance spectra.

However, to successfully use the state-dependent regression method, the exact knowledge of the underlying materials is not required and in many cases it is not even possible due to the high number of different bio-materials that shape the spectra at a given wavelength.

The wavelengths presented in this paper are not meant to be a process description, but to serve as the proof of concept. To fine tune the method for practical application more investigation is needed.

5 SUMMARY

Middle-aged beech and sessile oak trees have been investigated while slight drought (soil moisture deficit) has been simulated at half of the trees. Environmental parameters have been continuously monitored and the foliages have been sampled regularly to obtain UV-VIS-IR reflectance spectra of the leaves.

The state-dependent correlations at particular wavelength pairs in the reflectance spectra of foliage are sensitive to environmental variations. Changes in the environmental parameters, such as those of temperature or vapour pressure deficit, cause significant variations in the slope of the regression straight lines. The *sensitivity* of this variation, e.g. how big the slope change is for a given temperature rising, can be expressed by the *sensitivity for temperature change*. This *sensitivity*, in turn, varies with the soil moisture; the bigger the water deficit, the greater the absolute magnitude of the *sensitivity*. Therefore the slopes of the state-dependent regressions of some selected wavelengths are good indicators of the available soil moisture.

If the selected wavelengths are not directly sensitive to the water content of leaves, but measure some synthesized bio-materials, then the slopes represent the underlying metabolic regulation. In this way, the changes of *sensitivity* reflect the changes of metabolic regulation and its stability. The state and the stability of the regulation define the level of drought stress, summing up the long term effects of the environment.

This method applies the approach of state-dependent correlation for data analysis. This kind of correlation, due to the synchronous regulation of certain bio-material pairs, can be found in many biochemical processes. The exact qualification of materials influencing the reflectance spectra may be desirable but is not necessarily required. This is because it is not the material qualities but their amounts that determine the regression relationship at the selected wavelengths. The existence of state dependent correlation can be proved statistically without a priori knowing the materials involved. Moreover, as previous studies suggest, it might be utilized to assess not only drought stress, but many other environmental stress factors, too. However, it requires further investigation.

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Post-epidemic Situation of a Previously *Phytophthora alni*-infected Common Alder Stand

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Abstract – This paper reports on the current situation of the *Phytophthora* species occurring in a declining common alder (*Alnus glutinosa*) stand in North-West Hungary. The stand was affected by a severe epidemic caused by *Phytophthora alni* in the late 1990s. The authors evaluated the health condition of the forest stand and collected soil samples from the rhizosphere of twenty selected trees two times per year in 2011 and in 2012 in order to isolate *Phytophthora* species. A diverse *Phytophthora* community was found in the soil consisting of eight species with different aggressiveness and with different ecological demands. Pathogenicity tests confirmed the role of the collected strains in the decline of the alder stand.

Root and collar rot of alder / soilborne pathogen / *Phytophthora alni* / *Phytophthora taxon Raspberry* / *Phytophthora lacustris*

Kivonat – Egy korábban *Phytophthora alni* által fertőzött mézgáséger-állomány járvány utáni állapota. A tanulmány egy pusztuló nyugat-magyarországi mézgáséger- (*Alnus glutinosa*-) állományban jelenleg előforduló *Phytophthora*-fajokról, és azok faállományra gyakorolt hatásáról tudósít, egy korábban lezajlott, *Phytophthora alni* okozta súlyos járványt követően. A szerzők vizsgálták a faállomány egészségi állapotát, illetve talajmintákat gyűjtöttek a fák gyökérzónájából a *Phytophthora*-fajok kitenyésztése céljából. A vizsgálatokat 20 megjelölt fán végezték, 2011-ben és 2012-ben, évente 2–2 alkalommal. Az állományban változatos, eltérő agresszivitású és környezeti igényű fajokból álló *Phytophthora* közösséget találtak. A patogenitási tesztek igazolták a gyűjtött izolátumok szerepét az erdőpusztulásban.

éger gyökér és gyökfő betegsége / talajlakó kórokozó / *Phytophthora alni* / *Phytophthora taxon Raspberry* / *Phytophthora lacustris*

1 INTRODUCTION

A severe epidemical decline of common alder (*Alnus glutinosa*) trees was observed in South-England in the summer of 1993. An unknown *Phytophthora* species was isolated from the plant tissues and rhizosphere soil samples (Brasier et al. 1995). The previously unknown ‘alder *Phytophthora*’ spread epidemically throughout Europe in the last decade of the 20th century (Cech 1998, Werres et al. 1998, Szabó et al. 2000, Jung – Blaschke 2004, Cerny et al. 2008).

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The ‘alder *Phytophthora*’ is an interspecific hybrid, a series of phenotypically diverse, heteroploid genotypes coming from asexual hybridisation (Brasier et al. 1999). The species was described in 2004 as *P. alni* and the different variants were described as subspecies: *P. alni* ssp. *alni*, *P. alni* ssp. *multiformis* and *P. alni* ssp. *uniformis* (Brasier et al. 2004). The disease can occur in various habitats and in trees representing different ages. However, the primarily source of invasion might be the planting of infected saplings (Oszako 2010).

Other *Phytophthora* species were also isolated from the necrotic tissues or from the rhizosphere soil of infected alder trees. *P. citricola*, *P. cactorum*, *P. gonapodyides*, *P. megasperma* and *P. pseudosyringae* were isolated from necrotic tissues while *P. inundata*, *P. lacustris*, *P. plurivora*, *P. gregata*, *P. taxon hungarica* and *P. polonica* were isolated from rhizosphere soil (Szabó et al. 2013, Marçais – Husson 2014, Belbahri et al. 2006). These species may contribute to the decline of the alder stands (Szabó et al. 2013). However, they should not to be the main reason for the epidemic alder decline (Marçais – Husson 2014).

In 1999, a severe alder decline was observed near Csorna, North-West Hungary (Szabó et al. 2000). *P. alni* ssp. *uniformis* was isolated both from rhizosphere soil samples and necrotic root tissues (Szabó et al. 2000, Nagy et al. 2003). By 2003, the health condition of the alders improved gradually (Szabó et al. 2013). Instead of *P. alni*, clade 6 *Phytophthoras* were isolated from the rhizosphere soil samples (Szabó et al. 2013). This time, alder decline was observed at several other locations in Hungary (Koltay 2007). However, in addition to *P. alni*, other *Phytophthoras* were prevalent at these sites, too (Szabó et al. 2013). In the beginning of the 21st century, frequently isolated *Phytophthora* species from alder stands were *P. gonapodyides*, *P. plurivora*, *P. inundata*, *P. megasperma*, *P. lacustris*, *P. gregata* and two undescribed taxa, *P. taxon hungarica* and *Phytophthora* sp. 1. (Szabó et al. 2013).

Although, alder decline caused by the *P. alni* subspecies is well-studied, there are still some unanswered questions, especially about the ecology and evolution of the subspecies. What happens in the surviving forest stands afterwards is also an important question.

A diverse *Phytophthora* community occurs in the soil of the alder stands because of the favourable wet conditions (Szabó et al. 2013). However, we also lack information about the impact of other *Phytophthoras* on alder trees. Monitoring the health condition and *Phytophthora*-composition in these stands is necessary to predict a potential epidemic in time.

Herein, we present the results of a post-epidemic resurvey that was carried out in an alder forest severely attacked by *P. alni*. We also report on the differential pathogenicity of various *Phytophthora* species on alder saplings as a result of two kinds of inoculation methods.

2 MATERIALS AND METHODS

2.1 Evaluation of the health condition

Twenty common alder trees were selected for sampling in a thirty-three-year-old marshland forest near Csorna, West Hungary (Figure 1). The investigated forest stands grow on fen soil with permanent water effect. The evaluation of the health condition and the sampling was done in June and September of 2011 and 2012.

Specific symptoms of *Phytophthora* root and collar rot of alders, like bark necrosis often with a dark exudate, usually appear at the base of the trunk. The health condition of trees was evaluated based on the specific collar and secondary crown symptoms. To evaluate the severity of the crown and collar symptoms, five-point scales were used (Figure 2).

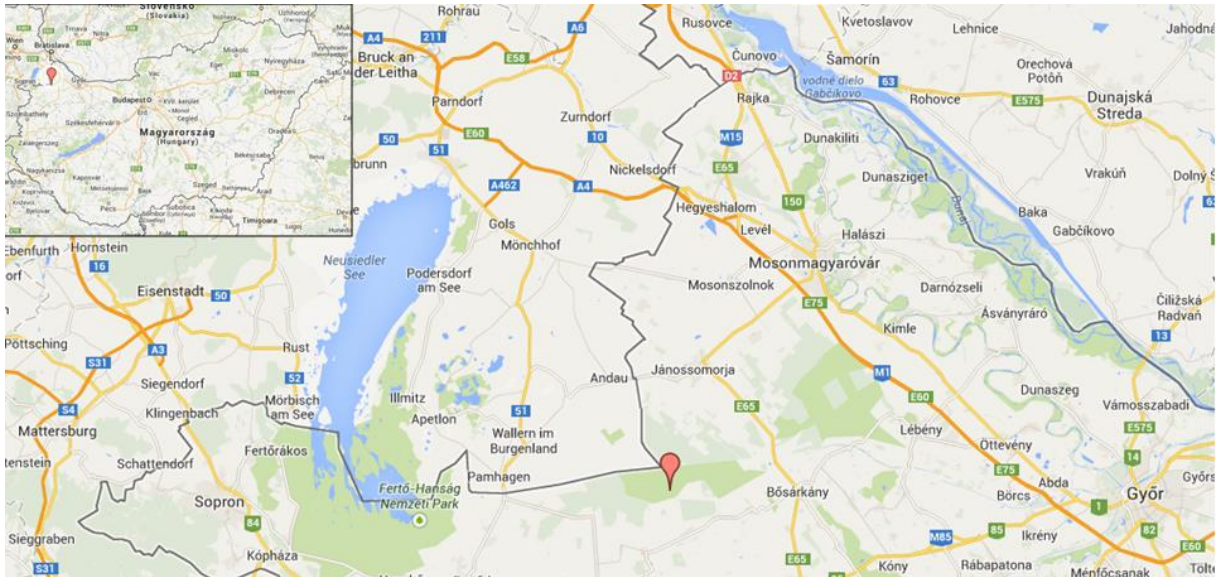


Figure 1. The sampling site. Source: Google Maps.



Figure 2. A1-A5: Health condition categories based on collar symptoms:

A1: Asymptomatic tree; A2: Bark necrosis covers less than 10% of the girth of the trunk horizontally and spreads vertically to a maximum 10% of the total height of the tree; A3: Bark necrosis covers 10–30% of the girth and height of the tree; A4: More than 30% of the total girth and height of the tree is damaged; A5: Dead tree.

B1-B5: Health condition categories based on crown symptoms:

B1: Healthy crown; B2: Less than 20% of the crown is dying. Some leaves are yellowish; B3: 20–50% of the crown is dying. Leaves with yellowish discolouration occur in groups. B4: More than 50% of the crown is dead. Yellow leaves in large groups, or the remaining foliage is yellow; B5: Dead tree.

2.2 Sampling, isolation and species identification

The method of soil sampling, sample processing and isolation were the same as reported earlier (Kovács et al. 2013). Identification of the collected isolates was based on morphological characteristics and specific molecular markers as described earlier (Kovács et al. 2013).

2.3 Pathogenicity tests

The pathogenicity of the following four most important species (collected in 2011) was tested: *P. alni*, *P. taxon Raspberry*, *P. inundata*, *P. lacustris*. Additionally, a *P. gonapodyides* strain was also tested because this species often occurred earlier in the rhizosphere soil of alders (Szabó et al. 2013). One representative isolate per *Phytophthora* species was used for inoculation. Inocula were collected from 14-day-old colonies grown on potato-dextrose agar plates (39g/L, Microtrade Ltd., Budapest, Hungary) in Petri dishes with a diameter of 90 mm.

One-year-old common alder saplings grown in plastic containers were infected. The soil for planting was tested for the lack of *Phytophthoras* using a leaf-baiting method.

Seventeen saplings per each isolate and corresponding controls (altogether 93 saplings) were wound-inoculated on April 26 and 27, 2013. A narrow wound with a length of approximately 5 mm was made on the base of the stem with a sterile scalpel and a 5 mm × 5 mm pathogen-infested agar plug was inserted in the wound. The wound was then sealed with Parafilm® (Pechiney Plastic Packaging Company). Control saplings had non-infested agar pieces in their wounds and were sealed as above. Another 17 saplings per isolate were used for root infestation (altogether 94 saplings including the control saplings). Altogether two pathogen colonies per sapling were put into the soil of the saplings at four positions around their stem.

The saplings were watered when necessary, and maintained under natural environmental conditions. After five months of incubation, disease severity of the saplings was evaluated based on five-point scales, 1 and 5 expressing no disease and lethality, respectively. In the case of the stem inoculations, the length and width [mm] of the bark lesion were measured. The average lesion size was calculated from the measured data based on the formula of an ellipsoid [mm²].

The health condition of the root system was evaluated based on a 5-point scale (Figure 3).



Figure 3: The scale for evaluating the health condition of the root system:

1. Healthy root system; 2. Root loss is below 30%; 3. 30–50% of the root system is lost;
4. Root loss is more than 50%; 5. Completely dead saplings.

The health condition of the shoots was evaluated based on a similar scale: 1. Symptomless sapling; 2. Some leaves are smaller than usual, occasionally with yellowish discolouration; 3. 30–50% of the potential crown is dead; 4. More than 50% of the potential crown is dead; 5. Completely dead saplings.

2.4 Data analysis

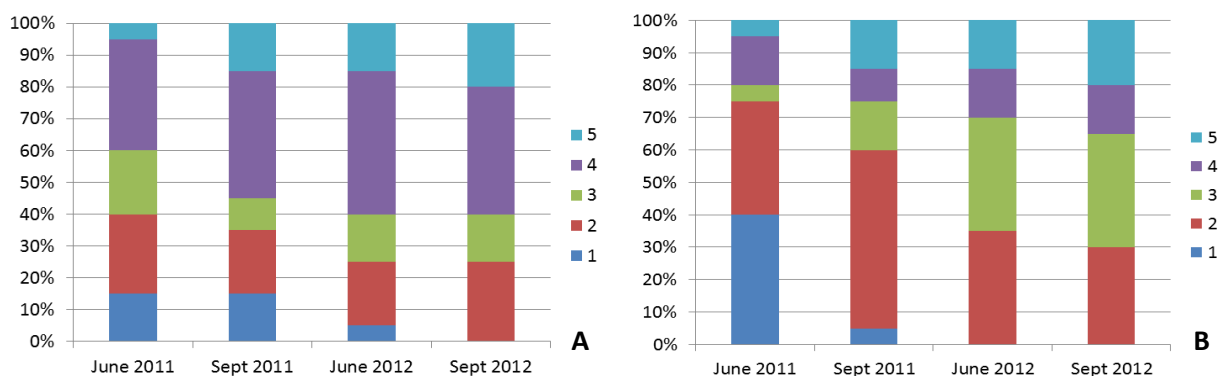
The health condition datasets were analysed with the Software STATISTICA (Ver. 11, StatSoft Inc. 2012). We used Kruskal-Wallis and Mann-Whitney tests to see the change in the health condition of our sampling site.

Data resulted from the pathogenicity tests were also analysed with STATISTICA. The Gaussian distribution of data sets was tested with the Shapiro-Wilks method. The homogeneity of variances of the variables was tested with Levene statistic, based on the median. Because the lesion size dataset does not have Gaussian distribution based on the results of the Shapiro-Wilks method, non-parametric tests were used to evaluate the pathogenicity. Kruskal-Wallis non-parametric ANOVA was used to compare multiple independent groups, and the Mann-Whitney U-test was used for pairwise comparisons of the treatment groups at $\alpha=0.05$ significance level.

3 RESULTS

3.1 Changes in the health condition

The health condition of the trees based on the bark symptoms (Figure 4A) did not change significantly during the experiment. Active lesions with fresh exudate could be observed altogether three times. Each time only one tree had fresh collar symptoms. However, the health condition of the trees based on the crown symptoms (Figure 4B) became considerably worse ($p=0.0053$) according to the Kruskal-Wallis test. Significant differences were observed between the results of June 2011 and 2012 ($p=0.0061$), and between the results obtained in June 2011 and September 2012 ($p=0.0029$). Changes are conspicuous in the decrease of the number of symptomless trees (from eight in June 2011 to zero in June and September 2012), and in the increase of the number of dead trees (from one in June 2011 to four in September 2012).



(1: best – 5: worst, details in the text)

Figure 4 A: Changes of the health condition based on the health condition categories of root collar and bark symptoms.

Figure 4 B: Changes of the health condition of the sampling site based on the health condition categories of crown symptoms.

3.2 Observed *Phytophthora* species composition

Figure 5 shows the observed species composition at different sampling times. Altogether nine *Phytophthora* taxa were isolated during the two-year survey: *P. alni* ssp. *multiformis*, *P. lacustris*, *P. taxon Raspberry*, *P. inundata*, *P. plurivora*, *P. polonica*, *Phytophthora* sp. *oaksoil*, *P. gonapodyides* and *Phytophthora* taxon *hungarica*. The most diverse species composition was observed in June 2011. Five different species, *P. alni* ssp. *multiformis*, *P. lacustris*, *P. taxon Raspberry*, *P. sp. oaksoil* and *P. inundata* were isolated at that time. Only

one species, *P. lacustris* was present at all times. *P. taxon Raspberry* was collected two times, in June 2011 and September 2012. The other species were found only once out of the four sampling times. They were present in the soil samples with low frequency.

Despite its low frequency, the presence of the highly aggressive *Phytophthora alni* in the rhizosphere soil of the trees is of great importance. At the very first sampling time, the *P. alni* ssp. *multiformis* was detected in the rhizosphere of two trees. However, at the other sampling times, we were unable to isolate this pathogen again.

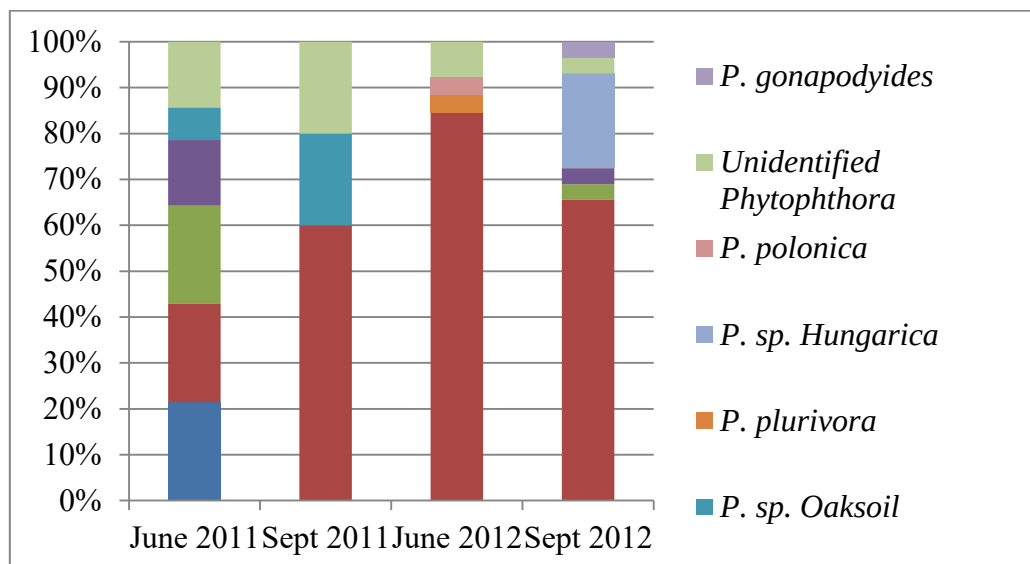


Figure 5: The observed species composition at the different sampling times.

3.3 Pathogenicity

3.3.1 Soil infestation test

Two out of 94 infected saplings died during the test period. Both saplings were infected with *P. alni* ssp. *multiformis*.

According to the results of the Kruskal-Wallis nonparametric ANOVA, the health condition of the roots of the saplings (Figure 6A) was significantly different between the groups with different treatments ($p=0.0000$). The soil infestation test did not result in significant differences in the health condition of the shoots during the test period ($p=0.0513$).

Based on the pairwise comparisons with the Mann-Whitney U-test, the health condition of the root system was worse in every infected group than it was in the non-infected control group. The most substantial damage was caused by the *P. alni* ssp. *multiformis* isolate ($p=0.0000$). Similar severe damage was caused by the *P. lacustris* ($p=0.0001$). The root system of the saplings infected with *P. taxon Raspberry* or *P. inundata* was also considerably weaker than the health condition of the roots of the control saplings ($p=0.0014$ and $p=0.0177$). However, the root system of *P. gonapodyides*-infected saplings was not significantly damaged in comparison with the root system of control saplings ($p=0.1497$). *P. alni* damaged the root system more severely than *P. taxon Raspberry* ($p=0.0293$), *P. inundata* ($p=0.0002$) or *P. gonapodyides* ($p=0.0001$). Damage caused by *P. inundata* was milder than that caused by *P. lacustris* ($p=0.0020$), but was not much different from the damage caused by *P. gonapodyides* ($p=0.4745$). *P. lacustris* caused significantly more severe damage to alder roots, than *P. gonapodyides* did ($p=0.0006$). The damage caused by *P. taxon Raspberry* did not differ greatly from the damage caused by *P. inundata* ($p=0.1729$), *P. lacustris* ($p=0.1434$) or *P. gonapodyides* ($p=0.0665$).

3.3.2 Stem inoculation test

Four out of 93 saplings, i.e. those inoculated with the *P. alni* ssp. *multiformis* isolate, died during the test period.

According to the results of the Kruskal-Wallis non-parametric ANOVA, the treatment groups differ to a great extent in terms of the health condition of the shoots of saplings ($p=0.0011$). As to the condition of the root system of saplings, there are also pronounced differences between the groups ($p=0.0007$), albeit the planting media of these saplings was not infected with *Phytophthora*. The lesion sizes (Figure 6. B) were also significantly different ($p=0.0000$) between the treatment groups.

Based on the pairwise comparisons with the Mann-Whitney U-test, the health condition of the shoots was the poorest in the *P. alni*-infected group. It was considerably poorer than in the non-infected control saplings ($p=0.0244$), as well as in the *P. taxon Raspberry*-infected ($p=0.0081$), the *P. gonapodyides*-infected ($p=0.0027$) and the *P. inundata*-infected ($p=0.0114$) groups.

However, based on the symptoms of the *P. alni*-infected group, the health condition of the saplings did not differ significantly from the health condition of the *P. lacustris*-infected group ($p=0.5228$). The health condition of the shoots in the *P. lacustris*-infected group were damaged much more than the shoots in the *P. taxon Raspberry* ($p=0.0380$), *P. gonapodyides* ($p=0.0131$) and *P. inundata*-infected ($p=0.0487$) groups.

Although only wound inoculation was carried out, there were notable differences in the health condition of the roots between the treatment groups. Based on the health condition of the root system, the most severe damage was caused by the *P. alni* ssp. *multiformis* isolate. The root systems of the saplings in the *P. alni* ssp. *multiformis*-inoculated group were significantly more degraded than the roots of the control saplings ($p=0.0114$), the *P. taxon Raspberry*-infected ($p=0.0401$) saplings and the *P. inundata*-infected ($p=0.0309$) saplings. Furthermore, *P. lacustris* caused substantial damage to the roots compared to the control saplings ($p=0.0177$). However, its impact was not significantly different from that of the other three *Phytophthora*s used for the inoculation test. *P. alni* ssp. *multiformis* and *P. lacustris* seem to be able to colonize roots secondary through the transport vessels of the sapling.

Every *Phytophthora* species used for the stem inoculation proved to be pathogenic to alder saplings ($p=0.0001$). The minimum, average, and maximum area of the lesions caused by the isolates used are summarized in Table 1. The lesions caused by the *P. alni* ssp. *multiformis* strain were considerably larger than those caused by *P. lacustris* ($p=0.0309$), *P. taxon Raspberry* ($p=0.0031$), *P. gonapodyides* ($p=0.0031$) and *P. inundata* ($p=0.0008$). The lesions caused by *P. lacustris* were also ascertainably larger than those caused by *P. taxon Raspberry* ($p=0.0027$), *P. gonapodyides* ($p=0.0040$) and *P. inundata* ($p=0.0001$).

Table 1: Average size of lesion caused by the species used for the wound inoculation experiment

Species	Area of lesion (mm ²)		
	minimum	average	maximum
<i>P. taxon Raspberry</i>	7.85	56.51	188.50
<i>P. alni</i> ssp. <i>multiformis</i>	0.00	502.32	1350.90
<i>P. gonapodyides</i>	0.00	45.61	
<i>P. inundata</i>	0.00	33.68	66.76
<i>P. lacustris</i>	31.42	132.59	522.29
Control	0.00	0.00	0.00

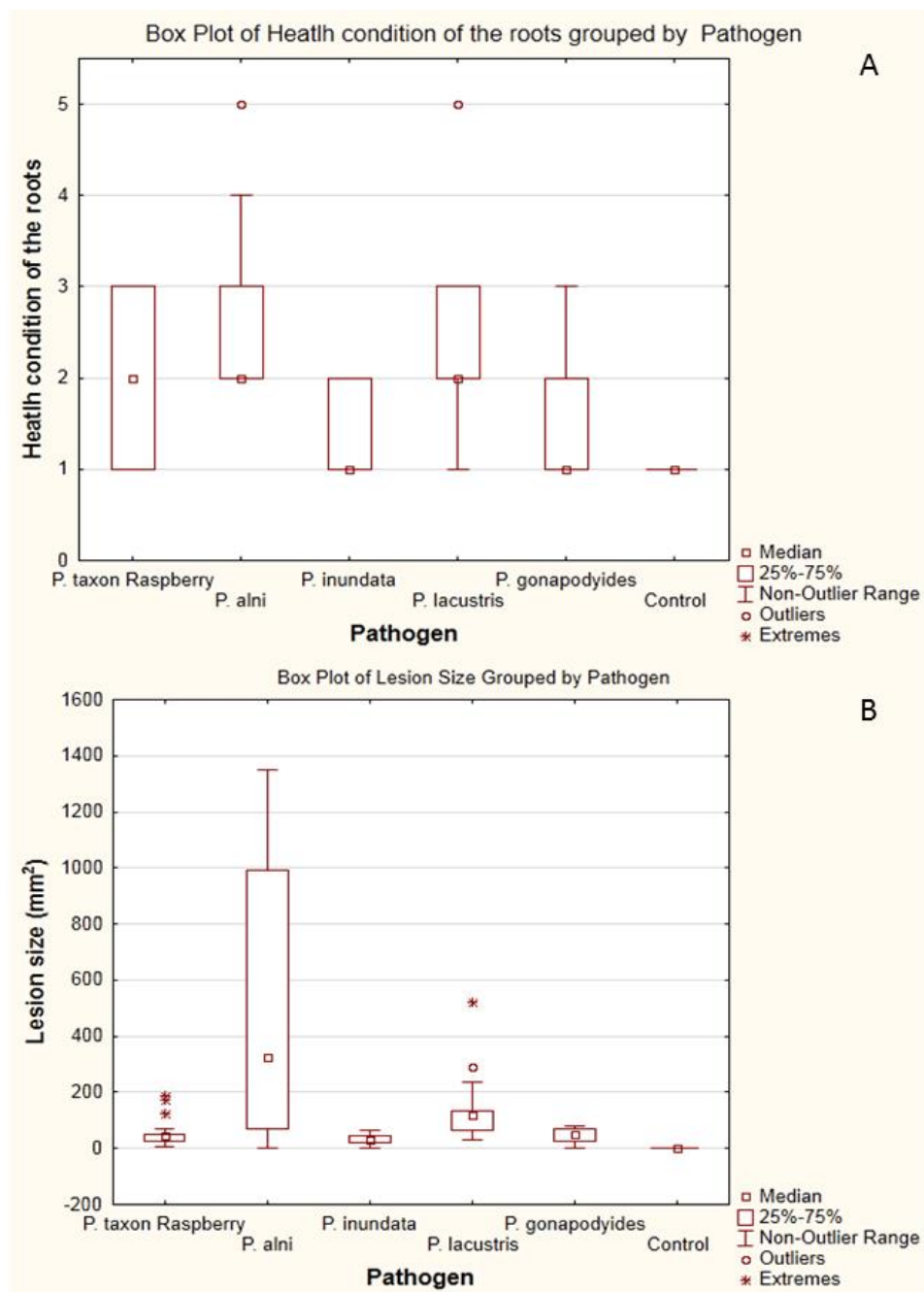


Figure 6: A: Health condition of the roots (soil infestation). B: Average size of the stem lesions (mm^2) caused by the different pathogens.

4 DISCUSSION

The collar symptoms of alder trees observed at the sampling site predominantly included cankers and tarry spots remaining from an earlier *Phytophthora alni*-infection. Active collar symptoms with fresh exudates were observed altogether on three different trees, at one sampling time each. This explains that the health condition of the trees seems to stagnate based on the dataset referring to collar symptoms. The observed crown symptoms are secondary symptoms ensuing from a potential root infection. The negative tendency of the health condition based on the crown symptoms, and the increasing number of dead trees may be in correlation with the *Phytophthora* species found in the rhizosphere of the investigated trees.

Both morphological and molecular methods were used to identify the collected isolates. Changes in the local composition of *Phytophthora* species were observed during the monitoring period. Weather extremities and changes in the soil moisture content may correlate stronger than seasonality to the observed alterations in species composition. Regarding *P. alni*, it has been isolated from the rhizosphere of two trees only, although it was not present in the soil between 2003 and 2008 (Szabó et al. 2013). In recent studies, we have isolated *P. alni* ssp. *multiformis*, whereas before 2003 *P. alni* ssp. *uniformis* was present in the stand. Based on the study of Marcais – Husson (2014), the presence of *P. alni* suggests that all trees on the studied site might again be attacked by *P. alni*. Conclusively, completely symptomless alder trees might harbour *P. alni* in their root system and as such they become the main inoculum source (Elegbede et al. 2010). Other *Phytophthoras*, like those in clade 6, are consistently dominant in forest soil with the permanent presence of water as was the case with our sampling area. However, *P. gonapodyides*, a species which had been multitudinous, was only once isolated during recent surveys while *P. lacustris* became the most frequently isolated *Phytophthora*. *P. lacustris* seems to be significantly more aggressive than *P. gonapodyides* on common alder. The new appearance of *P. alni* and the continuous presence of *P. lacustris* may explain the considerable condition decline based on crown symptoms of the trees in 2011.

The *Phytophthora* species chosen for the pathogenicity tests are soil-borne pathogens. They primarily damage the root system. Symptoms in the aboveground parts usually appear with a delay. This is why the soil infestation tests showed no significant differences in the health condition of the shoots, but they did reveal significant differences in condition of the root system between the treatment groups.

Among the studied *Phytophthoras*, the aggressive *P. alni* is able to infect trees through wounds or lenticels of the trunk. In this case, it damages the transport vessels in the roots and stem. The change of water and assimilates fails between the roots and the crown. The process leads to the death of the tree (Oßwald et al. 2014). This may explain the decline of root conditions in the *P. alni*-infected group in comparison with the other groups by the wound-inoculation test.

In a pathogenicity test Szabó and Lakatos (2008) used only the stem inoculation method on alder saplings with one isolate each of *P. gonapodyides*, *P. alni* ssp. *uniformis*, *P. inundata* and a then unknown taxon similar to *P. lacustris*. The average lesion size caused by that *P. gonapodyides* isolate was more than two times larger (93.49 mm^2) than the lesions caused by our isolate. This suggests quite a high intraspecific variation in aggressivity. Our *P. alni* ssp. *multiformis* isolate caused lesions that were almost three times larger than the ones caused by *P. alni* ssp. *uniformis* isolate (172.79 mm^2). The average lesion size caused by their *P. inundata* isolate (36.76 mm^2) is comparable to ours. Brasier and Kirk (2001) used, among other *Phytophthora* spp., *P. alni* and *P. gonapodyides* isolates for wound inoculations. In accordance with our results, they found that *P. alni* was the most aggressive *Phytophthora* species on common alder, while lesions caused by *P. gonapodyides* did not differ considerably from those on the control logs. Furthermore, Nechwatal et al. (2013) carried out both stem inoculations and soil infestations. In the case of root infection, both *P. gonapodyides* and *P. lacustris* significantly reduced the total dry mass of the roots of common alder saplings (Nechwatal et al. 2013). Both species caused similarly small lesions. The lesions did not differ much from those on the non-infected control saplings, while they were significantly smaller than the lesions caused by *P. alni* in their case study (Nechwatal et al. 2013). Our results with *P. gonapodyides* are well matched with their results, but with *P. lacustris*, our results suggest a higher intraspecific variability in pathogenicity.

P. inundata seems primarily to be a parasite of riparian woody species but also of some tree species like *Juglans regia* or *Prunus* spp. under horticultural circumstances (Brasier et al.

2003). In forest ecosystems, it was affiliated with root rot of olive (*Olea europea*) and species of the genera *Fagus*, *Castanea*, *Salix* and *Alnus* (Brasier et al. 2003, Safaiefarahani et al. 2013, Szabó – Lakatos 2013). It may cause the death of the host trees after heavy rainfalls and floods (Brasier et al. 2003). Therefore, after the extremely wet year of 2010, it is not surprising that we found *P. inundata* at our very first sampling..

P. taxon Raspberry is a clade 6 taxon, like its close relatives *P. lacustris*, *P. gonapodyides* and *P. inundata*. Data on pathogenicity tests with this species, however, are not available. Still, it is suggested that it may be an opportunistic pathogen similar to the other clade 6 species (Jung et al. 2011). The results of our pathogenicity tests support this hypothesis.

5 SUMMARY

A diverse *Phytophthora* community was present in the rhizosphere of the tested common alder trees. Of the eight species we found, only *P. lacustris* was isolated continuously. *P. sp. 'oaksoil'* and *P. taxon Raspberry* were found twice, while the other five species were only found once each. The highly aggressive *P. alni* was detected at the site again after more than ten years. At the very first sampling time, *P. alni* ssp. *multiformis* was isolated from the rhizosphere of two trees. However, earlier *P. alni* ssp. *uniformis* caused epidemic in the stand. Instead of *P. gonapodyides*, the more aggressive *P. lacustris* became the dominant *Phytophthora* species. *P. inundata*, *P. plurivora* and *P. taxon hungarica* were present in the soil, as earlier. However, instead of *P. megasperma*, *P. polonica* and *P. sp. 'oaksoil'* could be isolated.

Although there was no *Phytophthora*-epidemy observed at our representative sampling site, the decline of the trees was significant. Active collar symptoms were observed only in a few cases, while the number of dead trees increased and the health condition of the trees decreased, especially in the first year of our study.

Both pathogenicity tests confirmed the different pathogenicity of the isolated *Phytophthoras* on common alder saplings. Based on our results, the most aggressive *Phytophthora* pathogen of common alder is *P. alni*, while the second most aggressive is *P. lacustris*, followed by *P. taxon Raspberry* and *P. inundata*. *P. gonapodyides* was not confirmed to be pathogenic to alder roots. However, with its small lesions it proved to be slightly pathogenic to common alder saplings upon wound inoculations. Our results suggest that the appearance of *P. alni* and the continuous presence of *P. lacustris* may correlate with the decline of alders.

Our pathogenicity tests conclusively demonstrate the different pathogenicity of *Phytophthora* spp. on young alder saplings. However, their aggressiveness might be weaker on mature trees, thus the development of decline may be long-continued.

These results are based on a two-year-long field experiment, conducted in a representative sampling site of a marshland common alder forest. The changes observed during the survey period might also be true for similar forest stands surrounding the sampling site.

In order to fully understand the epidemiological and ecological aspects of alder decline, it might be necessary to correlate the abiotic environmental conditions of the sampling site with the observed results.

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Effect of Pavement Stiffness on the Shape of Deflection Bowl

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Abstract – The paper introduces a new method for calculating the elastic moduli of pavement layers. The method requires only two input parameters: the thickness of the upper „bound” layer and the Falling Weight Deflectometer (FWD) or Improved Benkelman Beam Apparatus (IBBA) measurement data. The authors developed a continuously differentiable regression function, which can be applied to describe the shape of the deflection bowl. Additional parameters of the deflection bowl (e.g. radius of curvature, position of inflexion point) can be calculated based on the regression function. FWD measurements were simulated running the BISAR (Bitumen Stress Analysis in Roads) software on different pavement variations. Outputs of the simulations were further processed with self-developed software. As a result, a series of diagrams were elaborated, by which the elastic moduli of the pavement layers can be determined.

Stiffness / pavement layers / elastic moduli / deflection bowl / BISAR

Kivonat – A pályaszerkezet merevségének hatása a behajlási teknő alakjára. Útpályaszerkezetek esetében a megfelelő rehabilitációs eljárás kiválasztása igen nagy gazdasági jelentőséggel bír. Ezért a szerkezetek állapotának megfelelő ismerete nélküli döntéshozatal igen költséges lehet. Emiatt különösen fontos, hogy az FWD (Falling Weight Deflectometer) vagy IBBA (Improved Benkelman Beam Apparatus) eszközzel mért elmozdulások elemzésével olyan többletinformációhoz jussunk, ami a döntést megkönnyíti a gyakorló mérnök számára. Az FWD vagy IBBA eszközzel mért deformációs vonalra illesztett függvényből levezetett görbületi sugár (R_0) és a burkolatvastagság (h) ismeretében a kötött rétegek alján jelentkező megnyúlásokat jól lehet becsülni. A BISAR (Bitumen Stress Analysis in Roads) programmal végzett számítások statisztikai elemzése pedig azt mutatja, hogy a D_0 (központi behajlás) és R_0 (görbületi sugár) paraméterek ismeretében lehetőség nyílik a kötött és szemcsés rétegek modulusának visszaszámolására.

Merevség / pályaszerkezet rétegek / rugalmassági modulus / behajlási teknő / BISAR

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INTRODUCTION

Forest roads with asphalt pavement represent the basis of the forest road networks in Hungary. Properly maintained asphalt pavements offer a high level of service. While traffic load of forest road networks have grown, expenses for their maintenance remained lower than required in the last three decades. As a result, these roads are in poor condition, generally. Renovation projects demand the knowledge of the roads' bearing capacity. The term "bearing capacity", although widely used at pavement management projects, is hard to define. In fact, direct measurement of bearing capacity is impossible. Instead, one can measure the deflection caused by a known load, and calculate the bearing capacity afterwards.

The traffic transfers its loads to road pavements through the tyres of the vehicles. Due to this, shearing stresses originate from vertical loads (pressing, beating, shaking, bending etc.) and horizontal stresses (braking, accelerating, wearing) (Kosztka 1978, 1986). These stresses affect each pavement layer differently, such as the elastic and plastic (permanent) deformation, the break and the structural realignment (Boromisza 1976). All these structural changes appear on the surface of the pavement as deformations, and the so-called deflection bowl or deformation surface forms.

To measure the evolving deformations several methods have been elaborated. Currently the measuring procedures based on absorbed oscillation are widely used. These are called Falling Weight Deflectometers, FWD. These deflectometers, operating with impulses, often drop a given weight from a given height onto a disc with anti-shock – using the potential energy – then they record the evolving displacements (Kosztka et. al. 2008). Researchers of the Institute of Geomatics and Civil Engineering at the University of West Hungary developed a new instrument to measure the full deflection bowl with the Benkelman beam (Markó et. al. 2013). The development was based on the Benkelman beam, extending its properties with automated data logging and the ability to measure multiple points of the deflection bowl. The Improved Benkelman Beam Apparatus (IBBA) continuously measures the vertical displacement of one point on the surface of the pavement, together with the horizontal position of the truck (*Figure 1*).



Figure 1. Falling Weight Deflectometer (left) and Improved Benkelman Beam Apparatus (right) in action.

The deflection bowl recorded during the test provides much more information about the current state of the pavement structure than the central deflection in itself. Therefore we can define its bearing capacity, remaining lifetime, and the thickness of the needed strengthening layer more precisely. Choosing the applicable rehabilitation procedure in the case of a given pavement structure has a really great economic significance. Without appropriately knowing the condition of the pavement, decisions could become very expensive. This is why it is so important to gain additional information by analysing the deflections, which makes it easier for the practising engineers to make decisions. We started our work with this approach, and summarized our results in this paper.

1 MATERIAL AND METHOD

1.1 Estimating the deflection bowl with functions

When deflection is measured to define the bearing capacity, displacements are measured and recorded only in certain distances from the load. This makes it necessary to fit functions onto the discrete measurement points to get the complete plot of all the evolved deflections. It is practical to apply functions describing the deflection bowl, because this way the geometrical attributes that are important regarding the stressed pavement can be defined with comparatively easy calculations.

Because of the surface sinking caused by mining (e.g. tunnel building), functions were already elaborated long time ago. Most authors (Aversin, Martos, Beyer, Bals etc.) suggested functions similar to the Gaussian bell curve (Fazekas 1978). Suggestions can be found to describe the deformation curve of pavements in Hothan and Schäfer's (2004) summary work.

Hossain (1991) used exponential function to estimate the deformation caused by external load:

$$D(x) = ae^{bx} \quad (1)$$

where x : distance from the centre of the load [m] and a, b : parameters.

On the basis of their examinations the effect of the upper and stiffer layers can be experienced in the decrease of the "a" parameter, while the effect of the lower high-solidity layers causes increasing "b" parameter value. The "a" and "b" parameters depend on the strength of materials characteristic of the pavement. The exponential function is able to estimate the FWD or IBBA measurements with high correlation, though it cannot reproduce the natural shape of the deflection bowl. Therefore it is not suggested to use it despite the high correlation coefficient.

Jendia (1995) tries to describe the whole deformation curve by substituting the exponential function in the central range of the deformation line $0 \leq x \leq r$ with a hexic polynomial:

$$D(x) = \begin{cases} c_3x^6 + c_2x^4 + \\ + c_1x^2 + c_0 & 0 \leq x \leq r \\ ae^{bx} & x \geq r \end{cases} \quad (2)$$

Jendia first defines "a" and "b" values of the unknown parameters. He specifies the second derivative's equality at the joint of the functions, that is, the continuity of the curve. Therefore, there are three constraints for the c_3, c_2, c_1 and c_0 parameter.

He creates the last independent variant iteratively by minimizing the difference between the values measured on the second and third sensor of the FWD device and the calculated deflections. The method of Jendia can reach only low equality with the data points in spite of its high demand of calculation (Figure 2).

Grätz (2001) makes it possible to describe the deflection bowl with a single function:

$$D(x) = \frac{w_a + w_b x^2}{1 + w_c x^2} \quad (3)$$

With the help of the suggested rational fractional function¹ the three factors that describe the whole bowl can be defined (Figure 2. Grätz (1)). The correspondence with the measured results can be further increased if a fourth degree of the polynomial is used:

¹ The rational fractional function is a mapping of the set of scalars, where we give the association with the quotient of two polynomials.

$$D(x) = \frac{w_a + w_b x^2 + w_c x^4}{1 + w_d x^2 + w_e x^4}. \quad (4)$$

Using the altered function higher correlation can be achieved, though the layer parameters cannot be concluded from the equation's factors as the coefficients depend on all the layers differently (Figure 2. Grätz (2)). To describe the deformation curve in practice, it is suggested to apply functions with which one bowl parameter can be deduced, which describes a special layer of the pavement (e.g. radius of curvature).

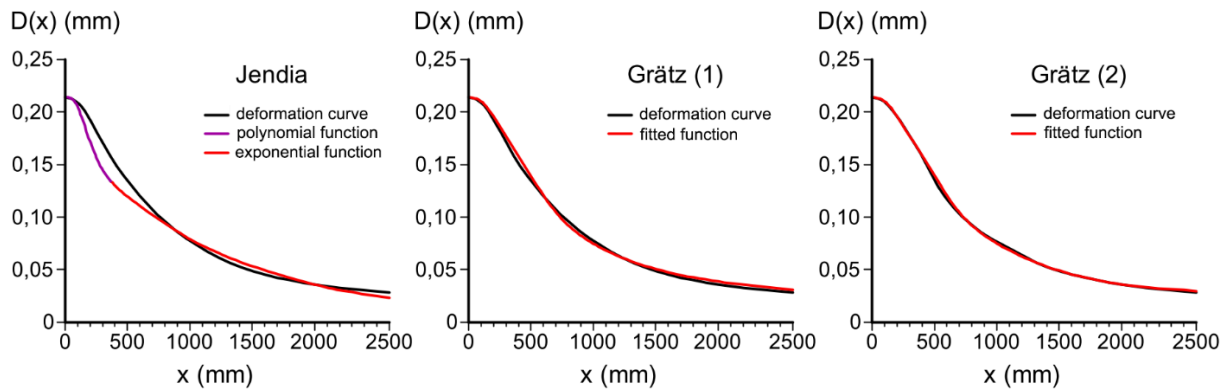


Figure 2. Comparing different deflection bowl functions (Hothan and Schäfer 2004)

In his study, Daehnert (2005) introduces two function types from the French literature (Ph. Leger and P. Autret) which shows good correspondence with the theoretical deformation curve:

$$D(x) = D_0 e^{-(x^2/b)} \quad (5)$$

and

$$D(x) = D_0 \frac{a}{x^2 + a} \quad (6)$$

where D_0 the maximum deflection in the axis of the load [m].

The function (6) was originally developed to process the Lacroix deflectograph data. In its structure, it is similar to the Agnesi² Witch Curve (Scharnitzky 1989). Cser (1961) uses function (6) to model the evolving deformations directly under wheel load with the substitution of $a = 3r^2$

$$D(x) = D_0 \frac{3r^2}{x^2 + 3r^2} \quad (7)$$

where r the radius of the loaded surface considered to be evenly dissolved and circle shaped [m]. The curve has an inflexion point at the edge of the wheel load ($x=r$). The function can follow the evolving deformations only in a restricted extent, as the inflexion point is fixed.

² Maria Gaetana Agnesi (Milan, May 16th, 1718 – Milan, January 9th, 1799), Italian linguist, mathematician and philosopher, the honorary member of the University of Bologna.

1.2 Estimating the deformation curve on the basis of mechanics functions

Starting with the Boussinesq stress formulas, the value of D_0 deflection under the centre of the $d = 2r$ diameter flexible circle plate can be deduced (Papagiannakis and Masad 2008):

$$D_0 = \frac{2pr}{E_e}(1 - \mu^2) \quad (8)$$

where

D_0 : vertical deflection measured in the load axis [mm],

E_e : the modulus of the flexible halfspace [MPa],

p : surface distributed load [MPa],

r : radius of the loading plate [mm],

m : the Poisson factor [-].

Beside the central deflection, Odemark calculated the deformation curve of the flexible halfspace with E_e modulus, loaded in the usual way using the $y = f(p, r, E_e)$ function. The second differential at its $x = 0$ point estimates the curve's value very well. The R_0 radius of curvature, in the case of one-layer half-space, can be calculated with the following formula (Nemesdy, 1985):

$$R_0 = \frac{E_e r}{p(1 - m^2)}. \quad (9)$$

Both functions give the same result in the case of homogeneous, infinite halfspace, so it is obvious that there is functional relation between the central deflection and the radius of curvature. Take the quotient of the equivalent modulus provided by the two equations:

$$c = \frac{2r^2}{R_0 D_0} \quad (10)$$

where “c” factor is the quotient of the two moduli, which is $c = 1$ in the case of homogeneous infinite half space.

It requires very long calculations to define deformations on the surface of the homogeneous half-space using Boussinesq's theory. Therefore, to simplify this, it is practical to take an estimating function. When determining the estimation function it is necessary to start from the geometric restrictions that are the boundary conditions. On the base of the above functions the following conditions can be stated: $x = 0$, where $D(x) = D_0$, and the second derivative $D''(x) \gg 1/R_0$ of the requested $D(x)$ function at $x = 0$. Additionally, the defined D_0 and R_0 values require mechanics conditions (10), too. Searching for the function that satisfies the conditions we start with the function type suggested by Cser (1961):

$$D(x) = D_0 \frac{d^2}{c \times x^2 + d^2} = D_0 \frac{1}{c \left(\frac{x}{d}\right)^2 + 1} \quad (11)$$

In the suggested function “c” is the so-called *shape factor*, which influences the shape of the deformation curve (Primusz – Tóth 2009; Primusz – Markó 2010). It can easily be seen that the estimation function really satisfies the $x = 0$ and $D(x) = D_0$ conditions. After defining the shape of the deflection bowl we can define the radius of curvature (*Figure 3*).

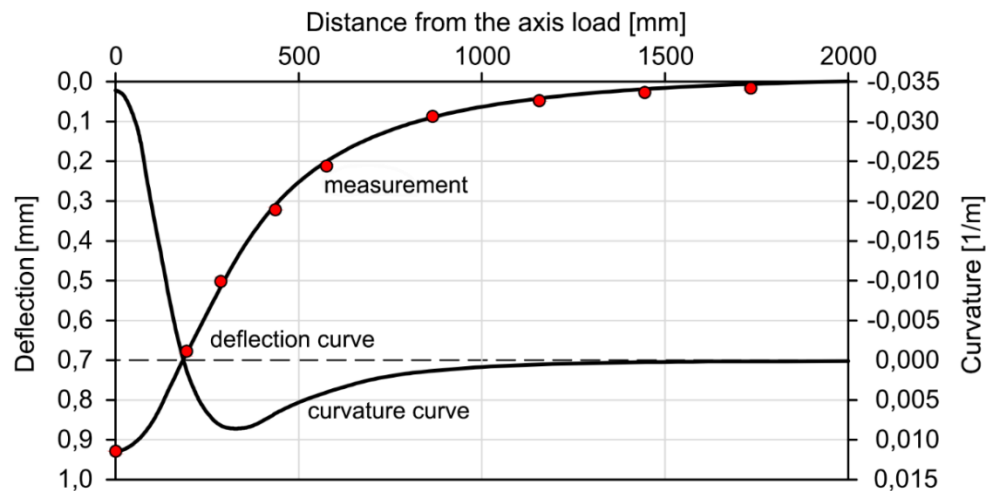


Figure 3. Curve of deflection bowl and curvature under load

We estimated the radius of curvature of the oscular circle belonging to an optional point of the $D = D(x)$ function with the $k(x) \gg D''(x)$ function:

$$k(x) \approx \frac{\vartheta^2}{\vartheta x^2} \left(\frac{D_0 4r^2}{cx^2 + 4r^2} \right) = 8 \frac{D_0 r^2 c (3cx^2 - 4r^2)}{(cx^2 + 4r^2)^2}. \quad (12)$$

The negative sign of the curve means that in the case of positive bending moment, the centre (0 point) of the oscular circle described with the curve radius is located on the $-D$ driven side of the axis. The curve alteration is presented in Figure 3. The minimal radius of curvature at $x = 0$ is

$$R_0 = \frac{2r^2}{D_0 c}. \quad (13)$$

It can be seen that the mechanics condition (10) is also satisfied, so the function is a good estimation of the mechanically defined deformation curve.

1.3 Estimation of the strain rising at the bottom of the bound layer

Knowing the radius of curvature derivated from the fitted function on the measured deformation points, and the thickness of the overlay, the strains rising at the bottom of the bound layers can be estimated with the following formula:

$$\varepsilon = \frac{h}{2R_0} = c \cdot D_0 \frac{h}{4r^2} \quad (14)$$

where

- ε : strain in the load axis,
- h : thickness of the bound layer,
- R_0 : radius of curvature in the load axis.

The conditions defined on the bound layer are satisfied if Hooke's law is present and the elastic modulus is equal for compression and for tension (Primusz – Tóth 2009).

1.4 Computer simulation with the BISAR software

The simulation is basically an examination where the expected and real behaviour of the system is being studied through the physical or computer model of a process.

Applying the simulation model we are able to provide appropriate inputs for the model of the system, operate it and observe the outputs.

Through the simulation of the pavements, we can observe what deformations evolve at the places of the sensors that record the deflections under external load, typical of the FWD devices, and how much stress evolves in each structural layer. Using the simulation, the deflection curve recorded on the pavements can be provided with more information, therefore, more exact pavement diagnostics are possible (Huang 2003).

1.4.1 Setting the simulation model

Nowadays, the most popular and most accepted method of defining the stresses evolving in pavements is the application of computer software. One of the oldest and most referred software is the BISAR (Bitumen Stress Analysis in Roads), developed by the SHELL Research Center. The software can calculate stress, strain, and deflection in an elastic multilayer system loaded with vertical load. The layers are characterized by their layer thickness, elastic modulus, Poisson factor and the adhesion defined at the boundaries of the layers. The whole system is supported by an infinite elastic half-space.

We used the DOS version of the BISAR software to carry out the simulation, because this way – after generating the starting data files – we could run batched calculations. The data files contained the structure of the pavements to be calculated in one procedure (number, thickness, modulus of layers etc.), the rate and place of load, and the coordinates of points where the calculation of stresses and strains are needed. The BISAR simulation ran in the case of two- and three-layer systems.

1.4.2 Pavement models used in simulation

The layers of the pavements can basically be divided into three groups: subgrade (together with frost protecting and/or improving layers), base layer, and overlay. Each group can be divided into further layers, so an average real pavement can be built of 3–5 layers (Figure 4. a). As to their material, the layers can be bound with bitumen (sometimes hydraulic) or can be unbound. As most pavement models are able to consider the material characteristics with the help of the elastic modulus and the Poisson factor, it is suggested to close up the unbound and bound layers and handle them as a whole instead of increasing the number of layers (Yoder – Witczak 1975).

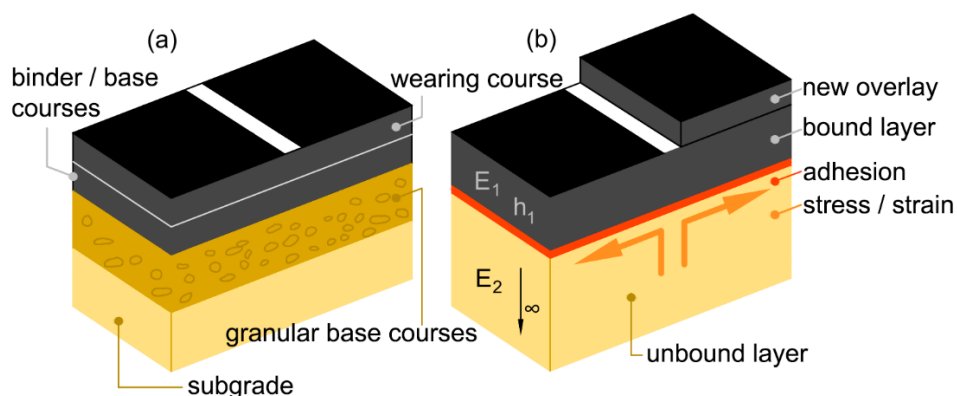


Figure 4. The structure of the pavement models in the simulations

Accordingly, bound and unbound pavement layers can be distinguished (Figure 4. b). The pavement behaviour models are able to consider the collaboration defined between the layers. Full slip should be assumed between the unbound granular layers and the bound overlays, while in the case of reinforcement – between the old and new overlays – full

adhesion should be expected, even if it causes smaller stress to the old asphalt layers. During simulation we examined the behaviour of the existing pavements with two-layer systems, while we used three-layer systems in the case of reinforced pavements. The two-layer systems are the idealized models of the existing pavements, in which the bottom layer refers to the unbound granular layers and subgrade, while the top bound layer refers to the overlays. There is probable frictional adhesion between the bound and unbound layers. In the case of the two-layer pavement models, the modulus of the top bound layer is between 1000 and 8000 MPa, the modulus of the bottom unbound half-space varied between 20 and 500 MPa. The thickness of the top bound layer varied between 50 and 500 mm, and we divided the examined range logarithmically examining 7 different values. Thus, we examined the two-layer systems in $12 \times 12 \times 7 = 1008$ combinations (Table 1).

Table 1. The parameters of the pavement models examined during simulation

Model	Nr.	Modulus	Var.	Poisson	Thickness	Var.	Adhesion	Sum
Two-layered	1	20 – 500	12	0,5	Infinite	–	1	1 008
	2	1000 – 8000	12	0,5	50–500	7		
Three-layered	1	20 – 500	12	0,5	Infinite	–	1	15 552
	2	1000 – 8000	12	0,5	50–300	6		
	3	5000 – 15000	3	0,5	20–120	6	0	

Notes: Layer ordinal (Nr.) from bottom to top, Layer-modulus (Modulus [MPa]), Variation (Var.), Poisson-factor [–], Thickness [mm], Adhesion [0: full adhesion, 1: full slip], All variations (Sum)

The three-layer models evolve from the two-layer systems with the addition of a reinforcement layer; this reinforcement layer can help in the examination of the bearing capacity of pavements. During calculations the rigidity modulus of the new asphalt layer used for reinforcement was 5000, 10000 and 15000 MPa. We then increased the thickness of the reinforcement layer by 2 cm up to 12 cm, so altogether 15552 variations evolved (Primusz – Markó 2010). Beside the layer modulus and thickness, the Poisson factor gets different values in the case of different materials; however, its practical definition is rather difficult as its value depends on tension and temperature (Pethő 2008; Szentpéteri – Tóth 2014). In the case of general road construction materials its value is usually between 0.2 and 0.5. The effect of the cross contraction factor's changes was examined in detail by De Jong, Peutz and Korswagen (1973), and Tam (1987). The researchers stated that changing the Poisson factor had little effect on the primary design parameters (strain, stress, deflection). That is, the effect on deflections caused by changing the Poisson factor is rather small compared to the layer thickness or the layer modulus. If the Poisson factor is increased from 0.2 to 0.5, the deflections will decrease by only few percent (Van Gurp 1995). Based on the above research in the BISAR simulation, we took each layer with the value $\mu = 0.5$. In this case, the analytical functions will largely be simplified; therefore, it is – in several respects – practical to choose this value.

1.4.3 Calculating stresses

The BISAR software is able to handle several loads and calculate their superposition. The loads and the examined points are placed in one frame of reference and can be arbitrarily defined by the x, y, z coordinate triplet. During the simulation we took size $F = 50$ kN single wheel load, which affects the top layer vertically, and scatters evenly a radius $r = 0.15$ m elastic circle plate ($p = 0.707$ MPa). The distance of the examined points – measured from the

load axis – was equal to the usual sensor set-up of the FWD device. In respect to the asphalt overlays' lifetime, the most important stress is the strain of the bottom edge line caused by the vertical deflection load. Therefore, in the fixed positions we examined not only the vertical deflections, but the strains defined on the bottom plane of the bound layers. After running the BISAR software, we evaluated the result text files with a self-developed program. We considered the vertical deflections calculated by the BISAR as a result of an FWD measurement during our further analysis.

2 RESULTS AND DISCUSSION

During the first part of the evaluation we examined how much effect each layer had on the evolving deformations in the case of a given pavement. This question is described in detail in Van Gorp's study (1995).

Figure 5 shows how much the layers of a three-layer structure effect the surface deflections (Van Gorp 1995). Naturally, the distribution changes with the modifying of the layer thickness or stiffness. According to the study, the thicker and stiffer the upper layers are, the more important the darkened areas of Figure 5 become. The figure demonstrates well that the bearing capacity of subgrade has the greatest influence on the peak value of the surface deflections, and 900 mm from the load axis, the measured deflection represents the deflection of the subgrade in 100%. It can also be observed that if we consider the subgrade and base layer as one, then the effect of the top bound (asphalt) layer expands only 300 mm from the load axis, so it mostly affects the central deflections.

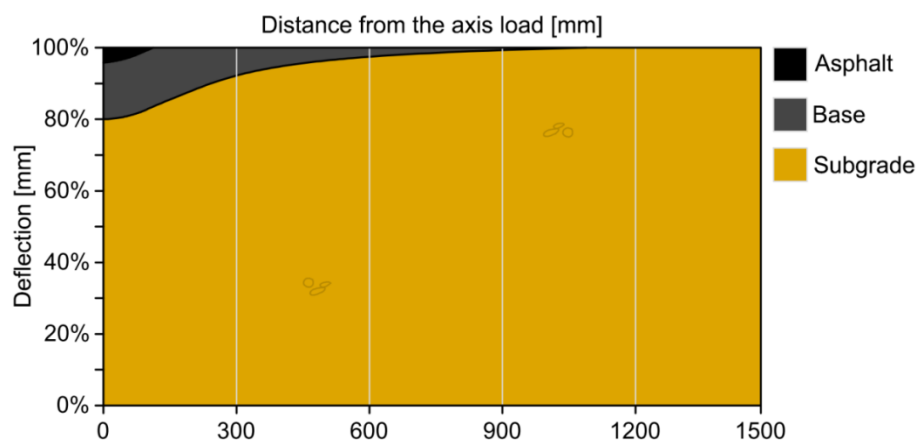


Figure 5. The effect of each layer on the surface deflection (Van Gorp 1995)

In the case of the examined pavement models, we calculated the maximum deflections on the surface, and also the partial deflections evolving at the bottom of the bound layer with the BISAR software. Thereby we had both deformation curves by structure. We fitted the function (11) onto these deflections, which resulted in two “c” shape factor values. By comparing the two values it can be stated that between the deformation curves evolving on the surface and at the bottom of the bound layer, the difference depends on the (h) layer thickness. This relation is graphically presented in Figure 6; the surface deformation curve is marked as c_t , while the one being at the bottom of the bound layer is marked as c_b (Figure 6. a). The thicker the bound layer is (h), the bigger the extent of the difference is (Figure 6. b). The differences of shape factors can be originated from the differences of deflections. Comparing the deflections of the 1008 two-layer systems, only the central deflections showed measurable differences in the range of 0–1 mm (70% of the D_0 values fell in between).

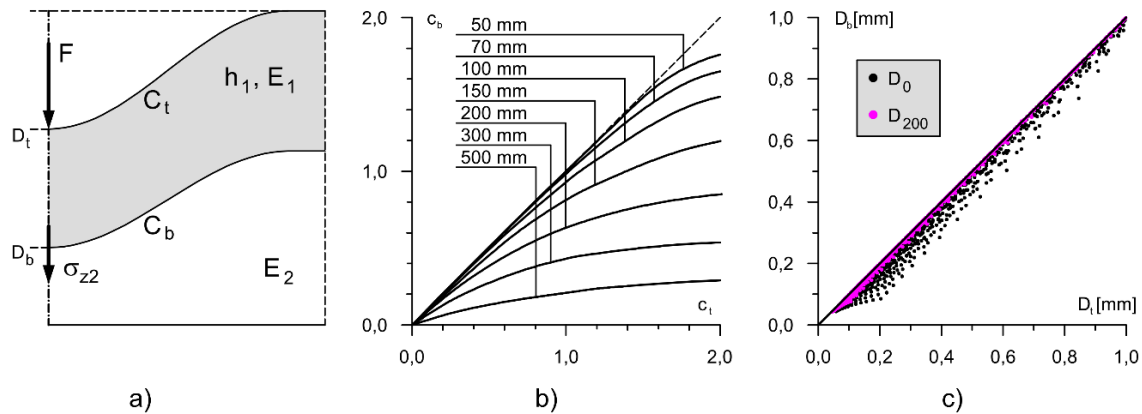


Figure 6. The changes of the “c” parameter of the function fitted onto the deformations evolving on the surface and at the bottom of the bound layer

Going farther from the load axis (200–300 mm) the deflections calculated on the surface and at the bottom of the bound layer were entirely the same (this result also confirms our statements at the beginning of this chapter). That is, the differences of shape factors can mainly be explained with the changes of the central deflection, as the thickness of the bound layer influences the compression of the layer itself (Figure 6. c).

Now, if we examine the results from the practical aspect and accept the assumption that the deflections measured on the pavement surface are nearly the same as the ones evolving at the bottom of the bound layer, that is $D_t(x) \approx D_b(x)$, then the shape factor (c_b) that characterizes the bottom of the bound layer can well be estimated on the base of the surface measurement: $c_t \approx c_b$. As the practical measurements always have the possibility of mistakes, and there are several factors (e.g. temperature) that modelling cannot count with, hereafter we will not make any difference between the two shape factors.

2.1 Analysis of the two-layer system

Using the results of the BISAR software we looked for relationship between the parameters deduced from the shape of the deflection bowl (Primusz and Tóth 2009), and the layer parameters of the two-layer system.

The examination revealed that the “c” shape factor, the quotients of the layer moduli (K) and the thickness of the bound layer (h) have very close correspondence. The graphical evaluation of the results is shown in Figure 7.

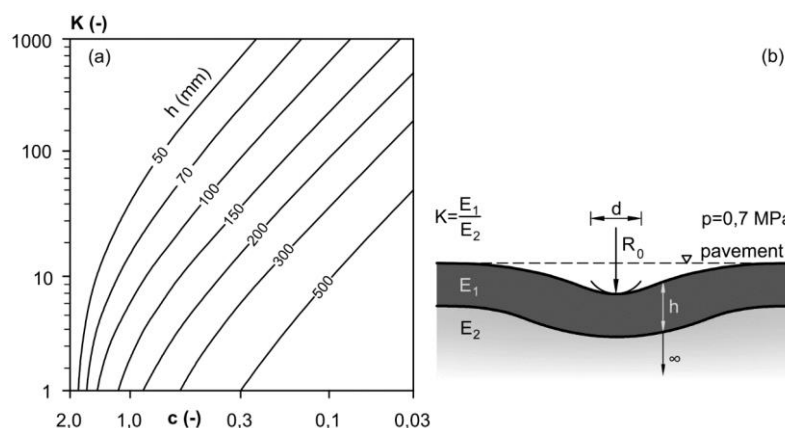


Figure 7. Function between the shape factor (c) and the rate of the layer moduli (K)

With the help of the graph the idealized two-layer model of a given pavement – knowing the bound layer thickness – can be induced from the FWD or IBBA measurements. We made the statistic model of the $K = f(c, h)$ function connection in two steps. The examinations showed that the rate of the K moduli and the σ_{z2} compressive stress evolving on top of the bottom layer are related similarly to the one in *Figure 7*. As the K and the σ_{z2} values do not depend on the accuracy of the function fitted on the deflections – that is the “c” shape factor – it is practical to first describe this relationship. We received the best result using the following model:

$$Y = \frac{a}{b \cdot X^c + 1} \quad (15)$$

with the next substitution: $Y = \sigma_{z2}$ and $X = h^d \sqrt{K}$. We defined the model's a , b , c and d parameters with the STATISTICA program:

$$\sigma_{z2} = \frac{0,8}{20,816 \cdot (h^{1,4} \sqrt{K})^{1,393} + 1} = \frac{0,8}{20,816 \cdot h^{1,95} K^{0,70} + 1} \quad (16)$$

The accuracy of fitting is clearly shown by the very high $R^2 = 0,9977$ value. Then we looked for a relation between the “c” shape factor and the σ_{z2} value. There was clear polynomial function with $R^2 = 1$:

$$\sigma_{z2} = 0,0392c^6 - 0,2749c^5 + 0,6907c^4 - 0,8332c^3 + 0,5424c^2 + 0,2588c \quad (17)$$

After plotting the value pairs, the hexic polynomial could be estimated with a line without the significant decrease of the fitting's rate ($R^2 = 0,9954$):

$$\sigma_{z2} \approx 0,4205 \cdot c. \quad (18)$$

Substituting function (18) in function (16), we get the wanted relationship:

$$c \approx \frac{1,9}{20,816 \cdot h^{1,95} K^{0,70} + 1} \quad (19)$$

or reordering to K :

$$K \approx 0,0131 \left[h^{-1,95} \left(\frac{1,9}{c} - 1 \right) \right]^{1,428} \quad (20)$$

the K factor here shows the stiffness of the layers correlated with each other.

2.2 Estimating the modulus of the granular layers

According to the study of Hoffmann (1988), if the pavement and the subgrade are considered as a two-layer system, knowing the radius of curvature and the central deflection, the E-modulus of the subgrade can be directly calculated. This statement can be checked knowing the results of the BISAR simulations. Using the deformation curves of the 1008 two-layer systems, the radius of curvature of the systems can be defined with the function (13). The related D_0 , R_0 and E_2 data rows are graphically presented in *Figure 8*.

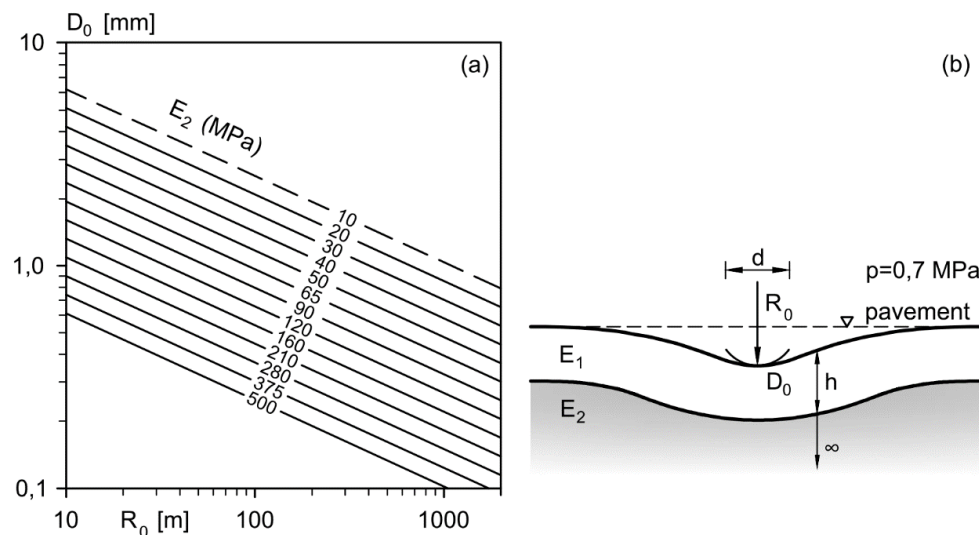


Figure 8. The E-modulus of the bottom layer can be defined by the centre deflection and the radius of curvature

Figure 8 shows that the data rows define a plane in dual logarithmic frame of reference. So the E-modulus of the bottom layer can be defined by the following function relation:

$$E_2 = a \cdot D_0^b \cdot R_0^c \quad (21)$$

The linear figure of the function:

$$\log(E_2) = \log(a) + b \log(D_0) + c \log(R_0) \quad (22)$$

The following general equation can be derived with the $Y = \log(E_2)$, $X_1 = \log(D_0)$, $X_2 = \log(R_0)$, $b_0 = \log(a)$, $b_1 = b$ and $b_2 = c$ substitution:

$$Y = b_0 + b_1 X_1 + b_2 X_2 \quad (23)$$

Here b_0 represents the intersection, while b_1 and b_2 show the partial slopes. The regression factors can be defined with the least square method as before (Orbay 1990). The results of the calculations made with the STATISTICA program are shown in Table 2.

Table 2. The statistic characteristics of the function constants fitted onto the two-layer system

h (cm)	N = 1008	β	Deviation (β)	B	Deviation (B)	t(1005)	p
Intersection		–	–	3.08794	0.000767	4024.03	0.00
5–50 Direction tangent (1)		–1.56581	0.000598	–1.62284	0.000620	–2617.99	0.00
Direction tangent (2)		–1.05669	0.000598	–0.62894	0.000356	–1766.77	0.00

$R^2 = 0.9998$, $F(2.1005) = 3515439$, $p < 0.0000$, $\alpha = 0.05$ and the residual deviation: 0.00525

According to the examination, there is very strong correspondence between the E-modulus of the bottom layer, the vertical deflection interpreted at the load axis, and the radius of curvature. The high R^2 also shows this. So the E_2 modulus can be estimated with the following function from the evolving deflections:

$$E_2 = 1224,45 \cdot D_0^{-1,623} R_0^{-0,629} \quad (24)$$

To avoid big numbers we gave the D_0 in millimetres, the R_0 radius of curvature in metres, while the joint modulus of the granular layers E_2 in MPa in the equation. According to the function (13) R_0 depends on the “c” shape factor, therefore, the (24) can be changed as follows:

$$E_2 = 111,73 \cdot D_0^{-0,994} \cdot c^{0,629} \quad (25)$$

According to the statistical model, it is not necessary to know the bound layer thickness to estimate the joint modulus of the granular layers, so it can be defined from the FWD or IBBA measurements without any destruction. The defined condition parameter may be useful especially for the Pavement Management Systems (PMS).

2.3 Estimating the modulus of the bound layers

The definition of the modulus of the bound layers is done using the following simple formula:

$$E_1 = K \cdot E_2 \quad (26)$$

where

- E_1 : modulus of the bound layer [MPa],
- E_2 : modulus of the unbound granular layer [MPa],
- K : rate of the layers compared to each other [–].

In the function (26), K is the rate of the bound and unbound layers compared to each other, which is calculated with the formula (20). To estimate the E_2 modulus we use the formula (24). Therefore we proved that in the case of two-layer pavement models, the moduli of the layers can unequivocally be calculated back from the deformation curve, so it is not necessary to use the iterative backcalculation methods.

2.4 Analysing the three-layer system

With the help of the BISAR software we modelled 15552 three-layer pavement variants. We calculated the evolving stresses and strains at the bottom of the reinforcement layers ‘built onto’ the original pavements and the whole bound layer thickness. The calculation was based on Ambrus’s (2001) former results. He demonstrated that at the bottom of the reinforcement layer of pavements having the same deflection curve but different structure, the same strains evolve in every case. That is, if the pavement deflection curve (its radius of curvature) is known, then the rate of the necessary reinforcement can be directly estimated.

We could not find regression relationship between the R_0 radius of curvature of the deflection curves calculated with the BISAR software and the strains evolving directly at the bottom of the reinforcement layer. The reason for this is that we assumed full adhesion between the two layers, so it actually behaved as one layer. Therefore, we later only dealt with the strains evolved at the bottom of the whole bound layer thickness. We managed to draw the following statistic model:

$$\log(\varepsilon_b) = -0,522 \cdot \log(R_0) - 0,533 \cdot \log(\Delta h) - 0,189 \cdot \log(E_{AC}) + 5,088 \quad (27)$$

or

$$\varepsilon_b = 122463 \cdot R_0^{-0,522} \cdot \Delta h^{-0,533} \cdot E_{AC}^{-0,1888} \quad (28)$$

where

- ε_b : strain evolving at the bottom of the bound layer after the reinforcement [$\mu\varepsilon$],
- R_0 : the radius of curvature of the pavement before the reinforcement [m],
- Δh : the thickness of the reinforcement layer between 20 and 120 mm,
- E_{AC} : the modulus of the reinforcement layer between 5000 and 15000 MPa.

The results of the calculations carried out with the STATISTICA software are shown in Table 3. Knowing ε_b , it is possible to define the necessary asphalt reinforcement layer. To do this, the asphalt fatigue functions used in asphalt mechanics have to be applied. The principle of the method is that the material is able to tolerate a certain strain during limited load repetitions without failure. That is why the evolving ε strain is equivalent with a repetition number, such as a unit axis crossing number (Ambrus 2001). The fatigue function of the material should be defined with laboratory examinations, though today, several estimating functions can be used (Bocz 2009).

Table 3. The statistic characteristics of the function constants fitted onto the three-layer system

h (cm)	N = 15 552	β	Deviation (β)	B	Deviation (B)	t(15548)	p
2–12	Intersection	–	–	5.08800	0.01863	273.09	0.00
	Direction tangent (R)	–0.83663	0.002617	–0.52207	0.00163	–319.69	0.00
	Direction tangent (H)	–0.42522	0.002617	–0.53302	0.00328	–162.49	0.00
	Direction tangent (E)	–0.11296	0.002617	–0.18882	0.00437	–43.16	0.00

$R^2 = 0.8935$, $F(3.15548) = 43491$, $p < 0.0000$, $\alpha = 0.05$ and the residual deviation : 0.10747

Currently in Hungarian road maintenance practice, the critical strain is defined directly at the bottom of the reinforcement layer. One reason for this is that the old asphalt layer becomes cracked, so we cannot count on its long-term load-bearing ability. This approach sometimes results in exaggeration, as it expects only the new layer to resist the external loads, while the old asphalt layers are still able to participate in the force-game. Counting with the existing asphalt layers is also hampered by the fact that only the fatigue ability of loose asphalt mixtures could be examined with 2- or 4-point bending test. It is very circuitous to make a test piece out of the core samples drilled out of existing pavement for these examinations. Today, the cracking-drawing test (Indirect Tensile Test, ITT) makes it possible to use samples directly drilled out of the pavement and define its fatigue characteristics (Pethő – Tóth 2012). The old asphalt material's fatigue criterion should be defined with the least squares method from the results of the laboratory experiment:

$$N_f = k \cdot \left(\frac{1}{\varepsilon_0} \right)^n \quad (29)$$

where

N_f : the entire load repetition number,

k, n : material constants,

ε_0 : horizontal strain in $\mu\epsilon$ in the centre of the test piece.

Based on the function (29) a statement can be made in connection with the strain of the old asphalt layer. The importance of the function (28) is that the strain can be estimated at the bottom of the existing asphalt layers after the reinforcement. Comparing the two functions the base function of a design procedure can be deduced, which will design upon the fatigue characteristics of the old rather than the new asphalt.

3 SUMMARY

The function suggested by us can be fitted not only onto deflection curves calculated with the FWD or IBBA, but also the ones calculated with the BISAR software. We showed that by knowing the deflection curve and the thickness of the bound layer, without using further

iteration procedures (backcalculation), we could define the modulus of the examined pavement's layers. The modulus calculated this way can certainly not be matched with the result of any laboratory tests. The practical benefit of the procedure is that with the defined moduli, we can create a pavement model whose behaviour – shape alterations under wheel load – well approximates the real pavement.

Knowing the radius of curvature we can calculate the strain of the bottom of the bound layer; knowing the strain, we can calculate the existing pavement's lifetime. The analysis of the three-layer models made it possible to estimate the strains evolving at the bottom of the existing asphalt layer after building the reinforcement layer, and so we can establish the theoretical possibility of a harmonic and economic reinforcement design method. The elaborated modelling procedure on the network level has the capability to be the base of a pavement management system. On the project level, the appropriately parameterized two-layer pavement model can help plan more professional reinforcement layers.

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Effects of Wood Ash on the Chemical Properties of Soil and Crop Vitality in Small Plot Experiments

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Abstract – Wood-burning power plants and heating plants produce a great amount of wood ash as a by-product of the combustion process. In 2009 we launched an experiment in which we examined the composition of ash, the nutrient supplying capacity of soil mixed with ash, and the availability of its constituents. In the spring of 2010, we conducted small plot experiments using wood ash applications equivalent to 0; 1; 2.5; 5 and 10 t of wood ash/ha, on slightly acidic clay loam soil using white mustard and rye grass as the test plants. The pH value of the soil rose in a statistically verifiable way as a result of the ash treatments. After the application of ash, the P₂O₅ and K₂O-content of the soil rose significantly; the treatments also increased the magnesium and sulphur content of the arable soil as well as the level of Zinc among the microelements. However, none of the wood ash applications caused verifiable changes in the number of shoots, in the green mass, or in the height of test plants. The increased nutrient supply of the soil through the treatments was not reflected in the nutrient content of the plants during the first year.

wood ash load / small plot experiment / nutrient supply / heavy metal content

Kivonat – Fahamu hatása a talaj kémiai jellemzőire és a termény vitalitására egy kisparcellás kísérletben. A fatüzelésű erőművekben és fűtőművekben az égetés melléktermékeként nagy mennyiségben keletkezik fahamu. 2009-ben indított kísérletsorozatunkban vizsgáltuk a hamu összetételét, a hamuval kevert talaj tápanyag-szolgáltató képességét, alkotórészeinek felvehetőségét. 2010 tavaszán szabadföldi kisparcellás kísérletet állítottunk be 0, 1, 2,5, 5, 10 t fahamu/ha-nak megfelelő dózissal fehér mustár és angol perje tesztnövényekkel, gyengén savanyú, agyagos vályogtalajon. A talaj vizes szuszpenzióban mért pH-értéke statisztikailag igazolhatóan növekedett a kezelések hatására. A hamu kijuttatásakor jelentősen emelkedett a talaj P₂O₅- és a K₂O-tartalma. A kezelések növelték a termőtalaj magnézium- és kén-tartalmát, valamint a mikroelemek közül a cink mennyiségét. A tesztnövények kelésszámában, zöldtömegében és magasságában egyik fahamu dózis sem okozott igazolható változást. A kezelések hatására a talajban megnövekedő tápelem kínálatot a növények tápanyagtartalma az első évben nem mutatta.

fahamu-kijuttatás / kisparcellás kísérlet / tápelem-ellátottság / nehézfém-tartalom

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1 INTRODUCTION

Interest in using biomass for energy has grown recently because of the reduced availability of fossil fuels. In recent years, a partial or complete switch to biomass heating solutions has happened in Hungary, both in regular households and in many coal-fired power plants such as the ones in Pécs and Ajka. (Tóth et al. 2011). For fuel, these power plants use firewood or sawdust and scrap wood from forestry and the wood industry.

The by-product of wood combustion is ash. The amount of combusted firewood is growing every year, which is consequently reflected in the increasing amount of wood ash. The annual estimated mass of wood ash in Hungary is 30 thousand tonnes; its volume is 50 thousand m³ (Tóth et al. 2011). Currently, wood ash is treated as waste and is most often used for filling former mine-shafts or it is simply landfilled. The growing expenses associated with landfilling and the reluctance to open new waste landfill sites have brought about increasing interest in alternative methods of disposal. Among these is the use of wood ash for the purposes of soil amelioration and soil refill in agriculture, horticulture, and forestry (Demeyer et al. 2001; Steenari – Lindqvist 1997; Zimmermann et al. 2010).

A variety of factors can influence the composition of wood ash. The quality of the combusted wood – whether it was scrap wood or of higher quality – can play a role as can the combustion technology used. (Campbell 1990). Which parts of trees are combusted can also influence the ash significantly; the nutrient content of roots and branches is much higher than the nutrient content of logs, for example. The difference between species can have significant effects, in many cases even within the same genus. In certain species the chemical compound of ash is normally influenced by the soil properties and the climate (Werkelin et al. 2005). The differences in the chemical composition of identical wood species from different stocks with acidic or calcareous soil may be bigger than in different wood species from stocks with identical soil qualities (Ulrich 1990). In addition to nutrients, ash might contain other elements such as heavy metals. Consequently, the data in literature concerning the chemical composition of wood ash is considerably diverse (Demeyer et al. 2001).

The application of wood ash can cause rapid changes in the chemical properties of the soil, especially in the top layer. The treatment can enhance the pH of the top layer by 0.3–2.4 units in a load of 1–7 t/ha (Mandre et al. 2006; Ozolincius et al. 2007; Perucci et al. 2008). In the deeper layers, the neutralizing effects are far more moderate, or they do not appear at all (Arvidsson et al. 2002). Oxides, hydroxides, hydrogen carbonates and carbonates are responsible for the rapid change in the pH level. The rate of hydroxide/hydrogen carbonates/carbonates ions can vary to a great extent, and consequently the alkalinisation effects of different ashes can also be diverse (Etiegni – Campbell 1991).

Ash contains all the components of wood in a concentrated form, except for carbon, hydrogen and nitrogen which evaporate during the firing of wood. The mean concentration of major nutrients in wood ash is as follows: 0.06% N, 0.42% P, 18% Ca, 0.97% Mg. Also, 2.27% of K for wood-fired boiler ashes (Vance 1996) and 1.57% P, 18.5% Ca, 2.86% Mg and 3.52% K for bark ashes have been reported (Someswhar 1996). During its application in soil, wood ash behaves like fertilizers with a low nitrogen content (NPK: 1:10:50) (Park et al. 2004). Its K-content perfectly dissolves in water, which explains its sensitivity to leaching (Demeyer et al. 2001; Odlare – Pell 2005). The greatest part of potassium gets bound in the soil both physically and chemically, and only 20 to 40% of potassium is available (Naylor – Schmidt 1989) when the potassium content in the soil is low. The calcium-oxide content of soil turns into calcium-hydroxide in the presence of water. Calcium-hydroxide reacts with the carbon-dioxide in the air, which results in the formation of calcium-carbonate. As a result, wood-ash enhances the lime content of the soil (Steenari et al. 1999).

The microelement concentration of wood ash is diverse. According to prior research, the heavy metal content of wood ash is typically low (Someshwar 1996). The increased pH-level in the soil will cause a further decrease in the mobilization of certain heavy metals. Despite the low concentration and the differences in mobility, heavy metals (Cd, Cr, Cu, Mn, Ni, Pb, Zn) may cause changes in the soil, vegetation and consequently in the composition of ground water (Ozolincius et al. 2007). Repeated spillage of ash may cause an accumulation of heavy metals. By lowering the soil pH, the mobilization of heavy metals will increase, which is a potential threat for the environment. However, wood ash has just the opposite effect on soil because it reduces the mobility of heavy metals (Vance 1996; Campbell 1990). According to the latest surveys, the toxic trace element load of the ash can fluctuate, so its Cd-content can reach a concentration of 20 mg/kg (Omil et al. 2007), like when the wood used comes from the soil of a spoil bank with high cadmium content and high acidity, for instance. In cases other than that, the accumulation of cadmium to such an extent is rare. Nevertheless, ash still needs to be used carefully in order to prevent heavy metal contamination or its incidental negative effects on terrestrial and aquatic ecosystems (Narodoslawsky – Obernberger 1996).

Application of ash on soil can be performed in several ways, and each way impacts the environment differently. Raw ash (as a strong alkaline) is difficult to manage as its particulates tend to dissolve easily. The particulate size of stabilized ash is larger, and as its pH-value is about 10.5, it is easier to manage, but at the same time – as it has a tendency to carbonation – the dissolution of nutrients is slow (Steenari – Lindqvist 1997). The pH of ash granules is lower, about 9, and its elements dissolve slowly due to the bigger particulate size (Callesen et al. 2007). Extruded, pelleted wood ash is also easy to manage thanks to its size, however, the dissolution of the elements is limited (Emilsson 2006; Csiha et al. 2007).

Wood ash is regarded as non-hazardous waste of non-agricultural origin, thus its use for agricultural purposes is an activity subject to prior authorisation. According to Act CXXIX of 2007, an application for an authorisation certificate must be submitted to the Directorate for Plant and Soil Protection of the relevant government office of a given county.

To examine the effect of wood ash on soil and vegetation we conducted a small plot experiment launched in May 2010. Within this framework we have been examining the composition of wood ash, the mobilization of its constituents, and its nutrient-supplying capacity. We have been studying the changes in the chemical properties of the soil as a result of the treatment, as well as the effect of the ash on the number of shoots, the growth and the element content in the test plants.

2 MATERIALS AND METHODS

The wood ash used in the experiment was collected in March 2010 from the ADA Hungária Bútorgyár Kft [ADA Hungária Furniture Factory Ltd.] in Körmend where scrap wood is disposed of through burning. Before the experiment was launched, the wood ash was stored in sealed plastic bags. We chose a slightly acidic soil for the experiment due to the alkalizing effect of wood ash. The agricultural plot selected for the experiment had an area of 100 m² and was located in Tanakajd, in Vas County. The designated land was divided into forty plots (1 m x 1 m / plot) to allow for the investigation of the effects of different loads of wood ash on ryegrass (*Lolium perenne*) and white mustard (*Sinapis alba*). The treatment groups were composed of a treatment-free control group and groups based on 1, 2.5, 5 and 10 tonnes of wood ash/ha with four replications for each treatment for both plant species (i.e. four replications per treatment per plant species). The treatment plots were arranged according to the laws of a randomized block design (Sváb 1981).

Of the two test plants, ryegrass responds intensely to changes in nutrient quantity, with rapid initial growth and strong germination. Ryegrass is commonly used for the testing of fertilizing effects for this reason. Seeds of white mustard show a rapid and nearly 100 per cent germination, which is why it can be used for testing anti-sprouting and germination inhibiting effects.

The preparation of each plot was followed by the application of the required amount of ash load, with the ash evenly mixed into the upper 10 cm layer of the soil. The test plants were seeded in May 2010. White mustard seeds were seeded on the 1 m² small plots, with 200 germinative seeds/m² and 25 cm spacing between each line, at a depth of 2–3 cm. Ryegrass seeds were dispersed on the 1 m² small plots, (40 grams of germinative seeds/m²) onto the surface of the soil, and subsequently worked into the soil to a depth of 1–2 cm. Rainy weather assured the water needs of the plants and no additional watering was required.

On the seventh day after planting, the number of sprouted white mustard plants was recorded for each plot. The white mustard and ryegrass plants were harvested in August (95 days after planting), at which point the number of plants per plot was recorded. In addition, the average height of the white mustard plants was determined based on the height of five randomly chosen plants. In the case of the ryegrass, we measured the average height of the plants. After the plants were cut off at the base, the above-ground biomass was measured per each plot, and subsequent to the harvest, we took samples of the white mustard test plants. Average samples from the replications were created for laboratory testing per treatment. Soil sampling also took place during the harvest. The samples were taken from depth of 0–10 cm, and consequently one average sample per treatment and replication was created. The laboratory-based analyses on wood ash, soil and plant samples were performed at the accredited soil protection laboratory of the Directorate for Plant and Soil Protection of the Vas County Government Office. The „total” element content of the wood ash, of the soil and of the white mustard test plants was determined following cc. HNO₃ + cc. H₂O₂ destruction, using Inductively Coupled Plasma. The soluble nutrient content of the soil was detected based on the method of Hungarian Standard MSZ 20135:1999.

Determination of easily soluble nitrogen fractions was made by means of extraction solvent 0.01M CaCl₂, while determination of soluble potassium and phosphorus fractions was performed by ammonium lactate solution (AL). For the extraction of the copper, manganese and zinc content ethylenediaminetetraacetic acid was used.

The statistical analysis was performed using software StatSoft, Inc. (2012), STATISTICA (data analysis software system), version 11. To explore the differences in the treatment effects, a one-way analysis of variance (ANOVA) was performed.

3 RESULTS

The ash mixed during the experiment is strongly alkaline, with a pH of 13.0. Its phosphorus content is 0.37%, calcium content is 23.29%, magnesium content is 2.68% and potassium content is 5.42% by weight. The iron content of the ash is significant too, 13.46 g/kg (*Table 1*). According to the test results it can be stated that the phosphorus content of the ash is lower than the values given in the literature (Etiégni – Campbell 1991), and the toxic heavy metal load did not exceed the values in the literature, with the exception of chromium.

The mechanical composition of the soil mixed for the experiment had the physical consistency of clayey loam, with slightly acidic pH, with no soda lime content, with nearly 27.3 per cent of clay-content (< 0.002 mm), and over 60 per cent of mud sediments in it (< 0.002 mm). According to its physical properties, the hydraulic conductivity of the soil is

average, while its water holding capacity is good and its air metabolism is satisfactory. Its nutrient content, based on its humus concentration, is good too.

Table 1. Characteristics and content of nutrients and heavy metals of wood ash.

Tested parameters	Units	Results	Results given in the literature (Etiégni – Campbell 1991)
pH (H ₂ O)		13.0	13.1 – 13.3
dry matter	% w/w	99.9	–
volume/mass	kg/dm ³	0.926	–
P	g/kg d.m.*	3.7	14.0
K	g/kg d.m.	54	41.3
Ca	g/kg d.m.	233	317
Mg	g/kg d.m.	27	22.5
Na	g/kg d.m.	5.8	3.4
Al	g/kg d.m.	18	23.65
Fe	mg/kg d.m.	13.5	19.5
Cd	mg/kg d.m.	6.5	21
Cr	mg/kg d.m.	182	86
Cu	mg/kg d.m.	110	145
Hg	mg/kg d.m.	< 0.5	–
Ni	mg/kg d.m.	58.9	–
Pb	mg/kg d.m.	85.0	130
Zn	mg/kg d.m.	496	700

Note: d.m.* - dry matter

The soil pH is favourable for the exposure to nutrients and thus for the nutrient uptake of plants, as this is a suitable pH-range for active biological life, with no extreme chemical conditions in the soil that would significantly lower the mineralization of any type of organic substances, macro- or micro-nutrients.

Due to the sum of the exchangeable cations in the soil, the overall cation exchange capacity of the soil (T-value) is good, 23.2 meq/100 g of soil. The good adsorption properties are formed as a result of the clay content and the humus content of the soil (*Table 2*). It is the colloids of the soil that are responsible for the water and nutrient absorption, as the amount of water stored in soil and available for uptake depends on the quantity and quality of colloids.

Table 2. Major characteristics of the soil used in the green-house experiments

Parameters	Results
pH (H ₂ O)	6.6
pH (KCl)	5.6
Plasticity index according to Arany (K _A)	43
Percentage of humus	2.6%
Percentage of carbonated lime	< 0.1%
Cation exchange capacity (T-value) (meq/100 g of soil)	23.2

In the case of the white mustard test plants, the treatments didn't cause a significant difference either in the number of all the emerged plants recorded on the seventh day, or in the number of plants per plot at the end of the trial period (*Table 3*).

Table 3. Effect of wood ash treatment on test plants.

Wood ash treatment (t/ha of soil)					Significant difference (5%)	Average
0	1	2.5	5	10		
White mustard, number of shoots (pc)						
182	181	184	180	179	10	181
White mustard, number of stocks (pc)						
180	179	186	183	183	7	182
White mustard, height (cm)						
120	121	122	120	121	8	121
White mustard, green mass (g)						
2543	2705	2430	2713	2663	919	2611
Ryegrass, height (cm)						
27	27	28	28	27	1.94	28
Ryegrass, green mass (g)						
802	830	821	848	864	107	833

According to the weight measurement of the different plots, the ash treatments provided a higher weight of organic material in both plant species on all plots, with the exception of one. There was no difference between the average growth in height within a species: white mustard reached an average height of 120–122 cm in each plot, while ryegrass reached 27–28 cm. The positive effects of wood ash treatment were manifested in the organic material content of the above-ground parts. When the white mustard was compared to the control group, the treatment of 1 t/ha caused 6.3% increase in weight, the treatment of 5 t/ha caused 6.7% increase, while the 10 t/ha treatment caused a growth of 4.7%. In the 2.5 t/ha treatment the green mass was lower than that of the control. A very similar tendency occurred with the ryegrass, too: when compared to the control, the 1 t/ha treatment resulted in a growth of 3.5%, the 2.5 t/ha treatment in a growth of 2.4%, the 5 t/ha treatment in a growth of 5.7%, while the 10 t/ha treatment caused an 8% growth in the above-ground organic matter. No significant change in the height and green mass of the test plants could be detected in any of the cases.

The ash treatment enhanced the soil pH measured in aqueous suspension. The pH value of the average soil-sample taken from an identically treated soil rose for both white mustard and ryegrass; after the application of a 10 t/ha dose, the pH level rose to 7.6, compared to the pH 6.4 level of the control. The values measured in the 1 mole KCl-suspension followed the pH-changes of water. No statistically verifiable differences in the pH-changes of the soil were uncovered for the two test plants: the pH values measured both in aqueous suspension and in suspension of potassium chloride seem to form a saturation curve (Figure 1).

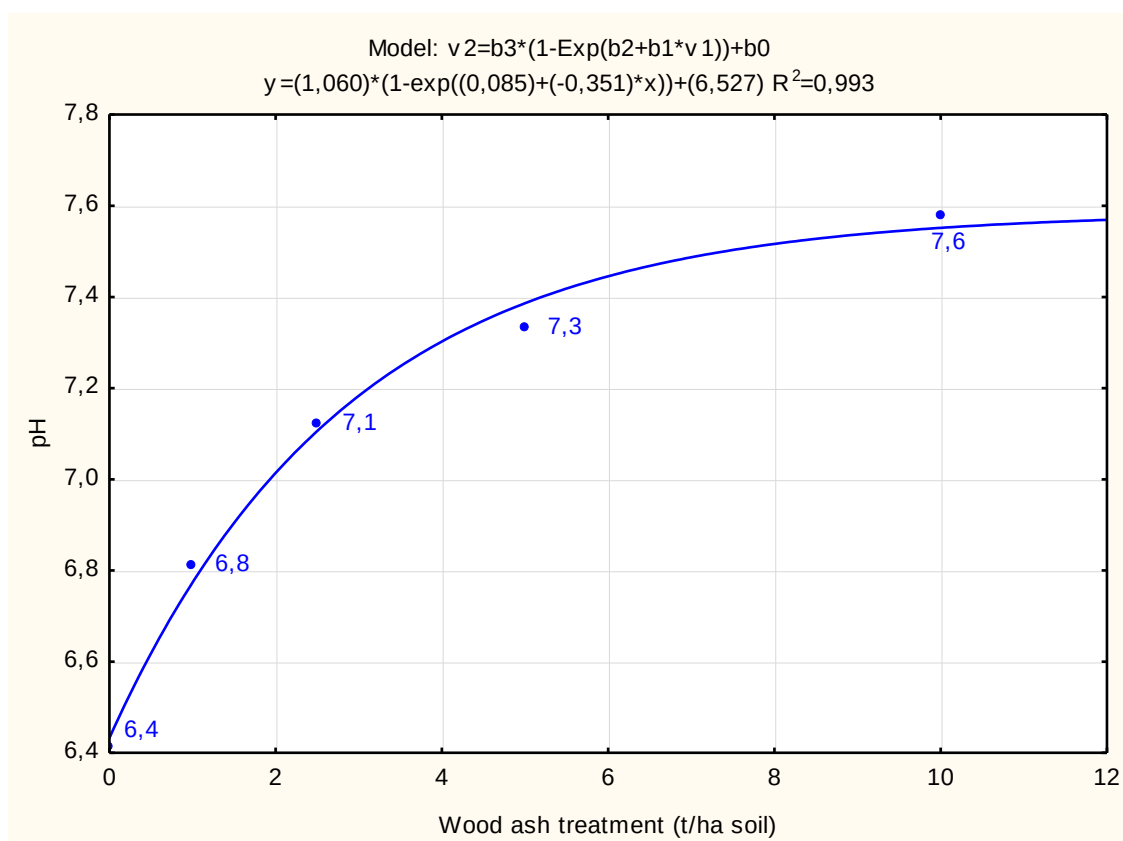


Figure 1. The pH-change in the soil of white mustard caused by the wood ash treatment

The ash treatment increased the carbonated lime content of the soil as well as the amount of potassium, phosphorus, magnesium and zinc, among the other nutrients. The carbonated lime content of the lime-defective soil rose to 0.8 mass% during the treatment of 10 t/ha. The treatment did not affect the amount of nitrogen, as this substance essentially evaporates during wood combustion.

The potassium content of the wood ash used in the experiment is equivalent to 653 kg of K_2O active substance per hectare. The AL-soluble K_2O content compared to the value of 301 mg/kg of the control increased up to 792 mg/kg, in the case of the highest dose in the 0–10 cm layer, so the potassium content of the originally well-supplied soil showed a further increase (limit value: 301–500 mg/kg).

The amount of phosphorus applied together with wood ash is equivalent to 85 kg P_2O_5 of active substance per hectare. The treatment caused a change in the P_2O_5 content from the value of 760 mg/kg to 1144 mg/kg in the 0–10 cm layer, thus the amount of phosphorus continued to increase in the especially well-supplied soil (limit value: 161–360).

The dosage of 10 t/ha enhanced the sulphate content of the top layer; its value changed to 35.6 mg/kg from the control's 11.9 value.

As a result of the ash treatment, the amount of magnesium in the soil with optimum magnesium supply (limit value: 100 <) increased to 398 mg/kg, from the initial 141 mg/kg (Buzás 1983). The EDTA-soluble zinc content of the control soil changed from the value of 5.3 mg/kg to 10.5 mg/kg after the wood ash treatment. In the case of copper and manganese no increase in concentration could be detected, while the amount of AL-soluble sodium content significantly rose after the wood ash treatment, reaching the value of 127 mg/kg, compared to the 36.0 mg/kg of the control. As to heavy metals, an increase in the amount of cadmium could be detected, with a change from 0.3 mg/kg to 0.5 mg/kg in the soil (Table 4).

Table 4. Effects of the wood ash treatment on the lime-, nutrient- and heavy metal-content in average soil samples

Parameters	Units	Doses of ash (t/ha)				
		0	1	2.5	5	10
CaCO ₃	% w/w	0.0	0.0	0.3	0.3	0.8
NO ₃ ⁻ +NO ₂ ⁻ -N	mg/kg	8.2	8.4	11.6	11.6	11.6
P ₂ O ₅	mg/kg	760	888	906	999	1144
K ₂ O	mg/kg	301	383	468	579	792
Na	mg/kg	36.0	56.0	71.0	95.0	127
Mg	mg/kg	141	148	237	305	398
SO ₄ ²⁻ -S	mg/kg	11.9	13.4	19.7	22.6	35.6
Ca	mg/kg d.m.	4648	5115	6187	6696	7435
Cd	mg/kg d.m.	0.3	0.4	0.4	0.5	0.5
Cr	mg/kg d.m.	37.2	38.5	38.2	38.2	40.1
Cu	mg/kg d.m.	21.5	22.5	22.8	23.3	23.3
Hg	mg/kg d.m.	< 1.5	< 1.5	< 1.5	< 1.5	< 1.5
Ni	mg/kg d.m.	25.7	27.1	26.5	25.8	27.3
Pb	mg/kg d.m.	28.9	30.4	30.7	30.8	31.8
Zn	mg/kg d.m.	82.7	87.5	89.0	90.6	93.3

The particulate content of white mustard test plants did not change significantly, which proves that the amount of nutrients in the untreated soil was initially suitable for the development of the plants. The amount of heavy metals in test plants did not change following the treatment (Table 5).

Table 5. Effects of the wood ash treatment on the average element content of the white mustard test plants.

Parameters	Units	Doses of ash (t/ha)				
		0	1	2.5	5	10
N	% w/w d.m.	2.6	1.9	2.3	1.6	1.5
P	% w/w d.m.	0.3	0.2	0.3	0.2	0.2
K	% w/w d.m.	2.1	2.1	2.0	1.9	1.6
S	% w/w d.m.	0.9	0.8	1.0	0.6	0.5
Cd	mg/kg d.m.	0.2	0.4	0.3	0.2	0.2
Cr	mg/kg d.m.	< 1.5	< 1.5	< 1.5	< 1.5	< 1.5
Cu	mg/kg d.m.	3.4	2.7	2.7	2.0	2.1
Hg	mg/kg d.m.	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
Ni	mg/kg d.m.	< 7.5	< 7.5	< 7.5	< 7.5	< 7.5
Pb	mg/kg d.m.	< 3.0	< 3.0	< 3.0	< 3.0	< 3.0
Zn	mg/kg d.m.	31.8	36.1	34.1	24.9	21.0

4 EVALUATION OF RESULTS AND CONCLUSION

During our research we examined the properties and chemical composition of wood ash. We studied its effect on the chemical condition and nutrient supplying properties of soil. Using white mustard and perennial ryegrass as test plants, we examined the effect of wood ash on the growth of test plants.

The laboratory tests revealed that wood ash has fairly high potassium, phosphorus and magnesium content, and its pH is highly alkaline. With one exception, the toxic heavy metal content of wood ash did not exceed the average values cited in literature (Etiégni – Campbell 1991). Wood ash has apparent effects on the soil. In the case of both test plants the dose of 10 t/ha raised the soil pH by approximately 1 unit. Regarding the nutrients, the nitrogen content of the soil did not change; however its potassium, phosphorus, sulphur, magnesium, calcium and zinc content increased following the ash treatment, as well as the lime content of the lime deficient soil. Among heavy metals, a slight increase in the cadmium amount could be detected, while the raised sodium content of the soil calls for further research.

The raised Na-content is unfavourable for cultivated plants, and its value exceeding 60 mg/kg is a sign of unfavourable salinization.

The treatment did not cause any statistically verifiable differences in the number of shoots and stocks or in the height and in the green mass of the test plants. Despite the fact that the above-ground organic matter grown on the different plots could not be detected with 95% level of significance, their amount increased by 3–8%, which means the plants were able to produce a greater amount of organic material from the excess amount of nutrients during a representative period of time. The plants experienced no toxic effects even with a maximum amount of ash-dose applied. The nutrient supply enhanced by the wood ash treatment was not reflected in the nutrient content of the plants. The test plants must have had an optimum nutrient supply at the time of the control, which would explain why the treatments did not cause significant differences. No significant change could be detected in the heavy metal content of the plants as a result of the wood-ash treatment.

Based on the conducted trials it can be stated that wood ash can effectively be used for agricultural purposes of amelioration of acidic soils instead of liming in order to reduce the acidification of soils with characteristics similar to those examined in the experiment. The experiments have proved that wood ash can successfully be used for purposes of nutrient supply. The ash must be applied and evenly mixed with the upper level of the soil before sowing; the recommended wood ash dose is 1 to 5 t/ha. With higher doses the P_2O_5 and K_2O -values measured in the soil would exceed the optimum values, which would cause the applied nutrients to be washed out of the topsoil in default of the needed colloid-content. In nitrogen-deficient soils, it is recommended to combine the application of wood-ash with N-fertilization.

Moreover, the agricultural application of wood ash has significant economic importance too. Application of ash on arable lands may lower the expenses of landfilling ash as waste. Utilization of wood ash, which is available in huge amounts, may partially replace expensive soil conditioners and fertilizers.

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The Influence of Wild Boars on the Growth of Forest Trees and Stands: A Case Study of a Wild Boar Game Preserve

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Abstract – This research investigated methods for determining and quantifying the impact of wild boars on the increment and growth of forest trees and stands. The influence of wild boars on stand variables was observed in a wild game preserve established in central Slovakia in 2000 practicing intensive wild boar management. Long-term measurements obtained from two long-term research plots of sessile oak trees established in 1969 were used to monitor stand growth. Increments of trees were observed on tree ring cores coming from trees surrounded by differently damaged soil surfaces. Wild boars rooting the soil surface proved to have neither a positive nor negative influence on the mean diameter and height of the forest stands. Analysis of radial increments in 9 trees growing on sites with more intense, deeper, and permanent rooting in the soil profile located near a larger mud bath was also carried out. A more distinctive increment depression was found on one oak near the mud bath and on one beech where deeper soil surface rooting occurred.

wild boar game preserve / game damage / tree ring analysis / radial increment

Kivonat – A vaddisznó hatása a fák és a faállomány növekedésére – egy vaddisznóskert esettanulmánya. Módszertani vizsgálatokat végeztünk annak megállapítására, hogy a vaddisznók jelenléte milyen hatással van a fák és a faállomány növekedésére. Vizsgálatainkat egy 2000-ben létrehozott vaddisznóskert területén végeztük. Kiindulási alapnak a területen 1969-ben létrehozott két kocsánytalan tölgy hosszútávú kísérleti terület adatait használtuk fel. Olyan mintafákból vettünk évgyűrű mintákat, melyek környezetében a vaddisznók a talajfelszín különböző mértékben kársították. A vaddisznók túrásának nem volt sem pozitív, sem negatív hatása a faállomány növekedésére. Kilenc további fa vizsgálatát is elvégeztük, melyeknél a talajfelszín túrása sokkal intenzívebb volt, illetve közelebb helyezkedtek el egy dagonyához. Itt egy tölgy és egy bükkfán figyeltünk meg jelentősebb növekedés csökkenést.

vaddisznóskert / vadkár / évgyűrű elemzés / átmérő növekedés

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1 INTRODUCTION

Forest stands are multifunctional communities of which wild game is an integral part. Though game populations and migrations generally occur naturally in forests, there are cases where game is unnaturally introduced into and supported within a restricted area. Game preserves are a good example of this. Economic considerations are at the forefront of most game preserves, but consequent increased game concentration per unit area and the possible negative influence on growth and production of forest stands must also be considered when introducing game into an environment. Published reports on forest stand damage caused by larger rodents (brown hare and wild rabbit) and also primarily by bigger mammals from the genus *Cervidae* (red deer, roe deer and fallow deer) (Ueckermann 1986, Náhlik 1995, Reimoser – Gossow 1996, Find’o 1998); Find’o – Petráš (2007, 2011) summarized current knowledge in this field. Therein, they provided a detailed ecological assessment of game living freely in natural environments including the feeding habits of the game and their negative influences on forest biotopes. These authors defined the extent of negative influence of game on forest stands and they instituted a methodology for damage calculation. Being cognizant of the latest knowledge on volume and value production of forest stands (Petráš – Mecko 1995, Petráš et al. 1996, Halaj – Petráš 1998), these authors also formulated the basis for this methodology. This was supplemented by experimental results of increment loss quantification following the browsing of young forest stand crowns (Find’o 1998) and also browsing and peeling of the bark from tree stems (Jöbstl 1987, Petráš 1996, Náhlik – Walter – Illés 1998, Čermák et al. 2009).

Although direct damage to crowns and stems by forest game has been relatively well studied, indirect methods of quantifying soil surface rooting and scarification of considerable portions of the soil profile were previously lacking. Wild boars are typically culprits of scarification; (Náhlik – Sándor 2003, 2005, 2012, Jánoska – Varju 2008). Find’o – Petráš (2007, 2011) quote this game on their list of animal species decreasing natural stand regeneration by excessive mast feeding. Within the concept of soil surface rooting, this game is more likely to be useful rather than harmful. These authors contend that better seed germination and better forest regeneration result in more favourable soil surface humidification. Although the intensity of soil surface rooting is not taken into consideration with this statement, this intensity certainly differs between wild boars living freely in the wild and those living in game enclosures.

The aim of this work is to investigate methods which will determine and quantify the impact of wild boars on the increment and growth of forest trees and stands. Specifically, in a wild boar game preserve with intense management. The focus is on observation of the wild boars’ influence on tree increments of more tree species and with respect to soil surface damage intensity in immediate proximity to those trees.

2 MATERIAL AND METHODS

The material for this study emanates from two sources. The first source consists of repeated measurements on two permanent sample plots established in 1969, and currently located within the game preserve. The second source is composed of tree ring cores taken from the most attacked sites of trees growing in the game preserve.

2.1 The wild boar preserve

The wild boar preserve is located in the central part of Slovakia, on a forest enterprise area owned by the Technical University in Zvolen. Its total area is 254 ha; 243 ha of which are

afforested. It was established in 1966–1971 to keep fallow deer, but in 2000 it was reworked to house wild boars. The population density of wild boars was increased gradually. In the first year there were only 6 boars, but after 5 years, their population increased to 215. The population is currently around 210–240 individuals, making the density 1 wild boar per 1.1–1.2 ha. As a result, the influence wild boars exert on forest stands was expected to occur after the period of 2000–2005.

The total area of the wild boar preserve is fenced. The game preserve is located at an altitude varying from 320 to 490 m. The growing season lasts 224 days, while the mean annual temperature is 10.9°C. This area receives 700 to 800 mm annual precipitation. SE to SW exposures prevail. The geological base is formed from andesite. There are middle-deep soils with 25–30% proportion of soil skeleton which rises up to the surface in some sites of the game preserve. Soil surface is covered with a thin layer of fallen leaves and in some places with thermophile plants and sparse brush undergrowth. The composition of the trees is 80% *Fageto quercetum* (FQ), 18% *Querceto fagetum* (QF) and 2% *Fagetum pauper* (Fp). sessile oak (*Quercus petraea* Liebl.) and the turkey oak (*Quercus cerris* L.) that are more than 70-years-old prevail throughout the entire game preserve. These tree species combined represent 65% of the tree species in the game preserve.

2.2 Long-term research plots

Two long-term research plots (LTP) were established to conduct long-term research on forest production and for construction of domestic yield tables in the 1969 state-wide programme. The sample plots are situated at approximately 400 m altitude. LTP No. 100 is 0.33 ha in area, and LTP 105 has 0.24 ha. Intense rooting of the soil surface caused by wild boars searching for food was determined by the last two measurements on both LTPs in 2005 and 2010. The sessile oak is the main tree species on sample plots, together with rare mixture of hornbeam (*Carpinus betulus* L.) and small-leaved lime (*Tilia cordata* Mill.). All trees on the sample plots are permanently numbered and each was repeatedly measured in 5-year intervals for diameter, sociological tree position, quality and mechanical stem damage. Although tree heights were generally recorded only during the first and last measurements, additional measurements were taken for height curve construction. Models of the height curves were derived from the Michajloff (1943) function:

$$h(d) = 1.3 + a \cdot \exp\left(\frac{-b}{d}\right) \quad (1)$$

where: h and d are for tree height and diameter,
 a and b indicate regression parameters.

A deviated position in some repeated measurements was discovered during detailed tree height analysis. Some height curves intersected and the distance between neighbouring curves was disproportionately large or small. Therefore, the following equation of Michajloff function modified by Petráš et al. (2012) was used:

$$h(d, t) = 1.3 + p_1 \cdot t^{p_2} \cdot \exp\left(\frac{-p_3 \cdot t^{p_4}}{d}\right) \quad (2)$$

where: h , d – tree height and diameter,
 t – stand age,
 p_1 – p_4 – regression parameters.

For its derivation, parameters a and b in equation (1) were expressed with dependence on stand age (t), and an independent regression model was derived from equation (2) for each LTP. The QC.Expert statistical package (Kupka 2003) was applied and the accuracy and precision of derived models was thus evaluated. Basic stand variables were calculated from

the number of trees in each 1 cm diameter class and from the height curve models. There were hectare variables such as the number of trees (N), the basal area (G) and the stand volume (V). Mean stem variables such as the tree mean volume (v), diameter (d_g) and height (h_g) and the same variables of upper stem were derived from those hectare variables. Their development was compared with the development of yield table models (Halaj – Petráš 1998).

2.3 Tree ring cores

Changes in tree growth were examined by tree ring series. Table 1 shows that 9 examined trees comprised 6 sessile oak (*Quercus petrea* Liebl.) trees, 2 silver firs (*Abies alba* Mill.) and 1 European beech (*Fagus silvatica*). While most of these trees were in a crown level position, with one being dominant and two intermediate, the crowns of two additional trees were cramped by neighbouring crowns. Tree rings were taken from trees growing on sites heavily attacked by wild boars. Seven trees are located at the position where wild boars both fed on supplementary given fodder and secured larger bedding. Another two trees are located at another site, near the bigger mud bath. One core was taken from each tree at breast height, and tree ring widths were measured by a digital positioner, connected on-line to a computer. Tree-ring series were synchronized, dated, and analysed in detail. Comparison was made between tree ring curves and variability of annual radial increments prior to 2000, before implementation of the game preserve for wild boars, and also after that period, when wild boars intensely influenced the plot. This research method was based on the work of several authors; primarily that of Fritts (1976), Schweingruber (1983), Pollanschütz (1986), Petráš et al. (1993) and Petráš – Mecko (2011). These authors confirmed that changes in growth conditions are best indicated by changes in radial increments; where trees form thinner tree rings with lower variability in worsening growth conditions, and vice versa.

Table 1. Basic data on trees of which tree ring cores were taken

Number of the tree	Tree species	Tree diameter d (cm)	Tree class	Crown	Notice
1	oak	47	2	free	
2	oak	35	2	suppressed	
3	fir	35	3	free	
4	oak	33	2	suppressed	
5	fir	72	1	free	
6	oak	43	2	free	
7	beech	39	3	free	
8	oak	46	2	free	at the mud bath
9	oak	41	2	free	at the mud bath

3 RESULTS AND DISCUSSION

3.1 Changes in oak stands growth

Measured tree heights were individually equalized for each LTP, dependent on their stand diameter and height, using nonlinear least squares in compliance with the model (2). One height measurement proved incorrect for each LTP. The following systematic methods were employed. (1) On LTP 100, tree heights were lowered on the fourth measurement by approximately 1.0–1.5 m, and (2) on LTP 105, higher heights were measured on the first occasion. In both cases, these measurements were excluded from the regression equation. The

equation parameters (Table 2) are very favourable. Determination coefficients R^2 are relatively high and these reveal that the model explains 93–95% of observed height variability. Standard errors of the equation are relatively low s_h (1.13–1.32 m) for the same reason. The model height curves (Figure 1) have a typical fan shape, where tree heights increase non-linearly with broader diameter and higher stand age.

Table 2. Parameters ($p_1 - p_2$) and statistical characteristics of regression equation of height curves models

Plot	p_1	p_2	p_3	p_4	n	R	R^2	s_h (m)
LTP 100	2.1186	0.6390	0.5211	0.6732	905	0.9632	0.928	1.32
LTP 105	0.9495	0.7999	0.3479	0.7550	656	0.9761	0.953	1.13

Note: LTP – long-term research plots; n – number of measured heights;
R – correlation coefficient; R^2 – coefficient of determination; s_h – standard errors.

Table 3. Development of basic stand variables from repeated measurements on LTP

Year of measurement	Age	Values per 1 ha			Mean stem			Upper stem (10%)		
		V	N	G	v	d	h	v	d	h
		(m ³)	(pcs)	(m ²)	(m ³)	(cm)	(m)	(m ³)	(cm)	(m)
LTP 100										
1969	56	194	1318	27.26	0.147	16.39	18.50	0.385	24.18	21.37
1974	61	211	1179	27.67	0.179	17.50	19.53	0.488	26.33	22.68
1979	66	231	923	27.60	0.250	19.74	21.10	0.660	29.49	24.20
1984	71	268	801	29.70	0.335	21.97	22.55	0.837	32.23	25.58
1995	82	345	687	34.07	0.503	25.41	25.10	1.194	36.62	28.15
2005	93	435	638	39.36	0.682	28.31	27.29	1.619	40.88	30.60
2010	98	474	605	41.33	0.784	29.79	28.34	1.833	42.76	31.67
LTP 105										
1969	48	102	3881	26.30	0.026	9.70	12.10	0.109	15.90	15.28
1974	53	122	3522	27.29	0.035	10.50	13.01	0.153	17.77	16.66
1979	58	145	2312	26.48	0.063	12.60	14.77	0.237	20.75	18.35
1984	63	177	1723	27.64	0.102	14.75	16.53	0.341	23.61	19.95
1995	73	255	1314	32.96	0.194	18.29	19.37	0.545	27.77	22.63
1999	78	286	1032	34.02	0.277	20.76	21.10	0.648	29.44	23.85
2005	84	340	973	37.68	0.350	22.47	22.48	0.805	31.74	25.38
2010	89	379	898	39.71	0.422	23.98	23.69	0.934	33.39	26.57

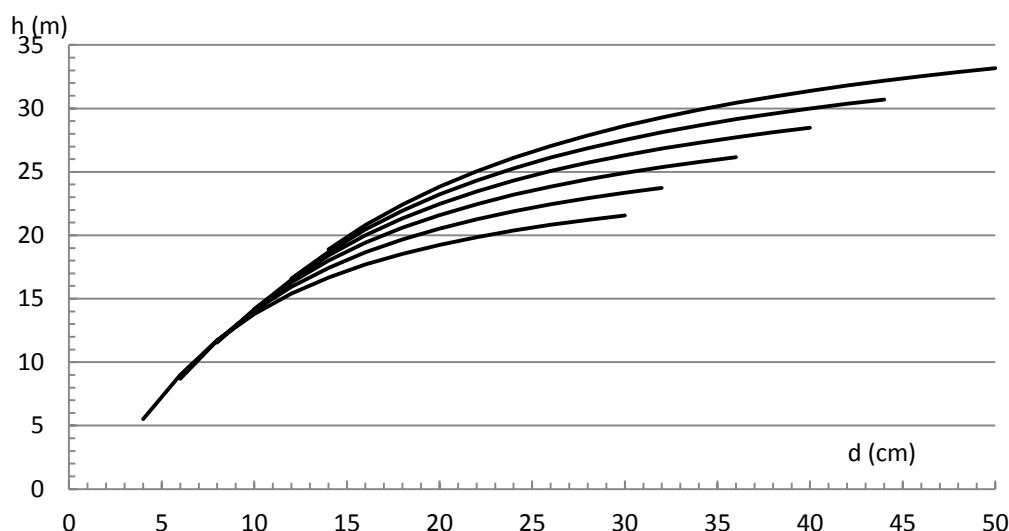


Figure 1. Height curves model for trees 50–100 years old on the LTP 100

Oak stand growth was evaluated by the continuous development of their growth variables (Table 3). Although hectare variables such as the number of trees (N), the basal area (G) and the stand volume (V) result from growth processes, these also significantly depend on stand density. More remarkable negative influence of wild boars on the density of mature stands cannot be expected at a wild boar density of 0.83–0.94 per 1 ha of the game preserve, only on the growth conditions of individual trees, so their influence was assessed via changes in tree mean diameter (d_g in Figure 2) and mean height (h_g in Figure 3). Development of these characteristics on both LTPs was compared with model development yield tables (Halaj – Petráš 1998), and thus LTP 100 was assigned to site class 26 and LTP 105 to class 22. However, the actual mean diameters, and especially the mean heights, displayed a more abrupt course on these LTP than that in the model yield tables. Following the establishment of the game preserve in the year 2000, increased significant influence of wild boars on the stands growth was expected. At that time, LTP 100 was approximately 90-years-old and LTP 105 was 80. However, comparison of the actual and the model curves failed to definitively prove that wild boars negatively or positively influenced the growth process of oak stands through trampling effects on the soil surface.

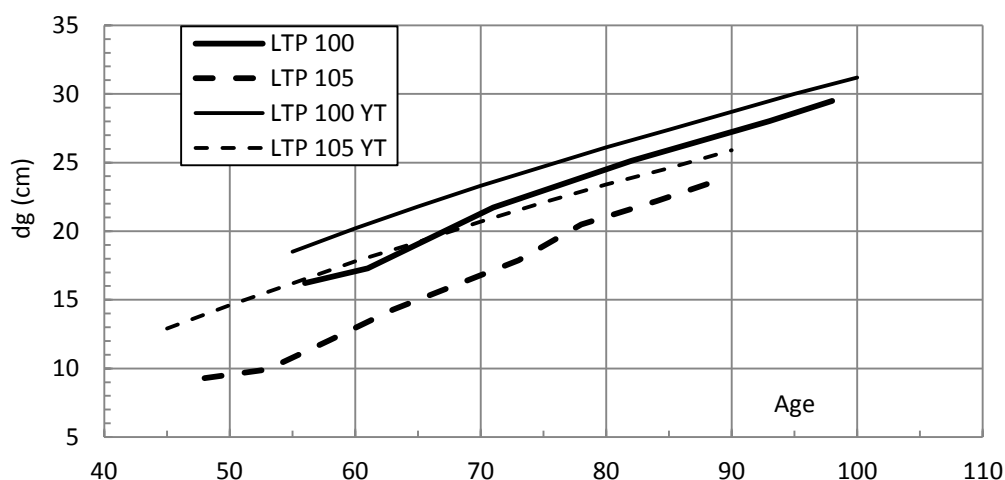


Figure 2. Comparison of mean diameter d_g development (bold) on LTP 100 and 105 with the model one (thin) by yield tables (Halaj – Petráš 1998)

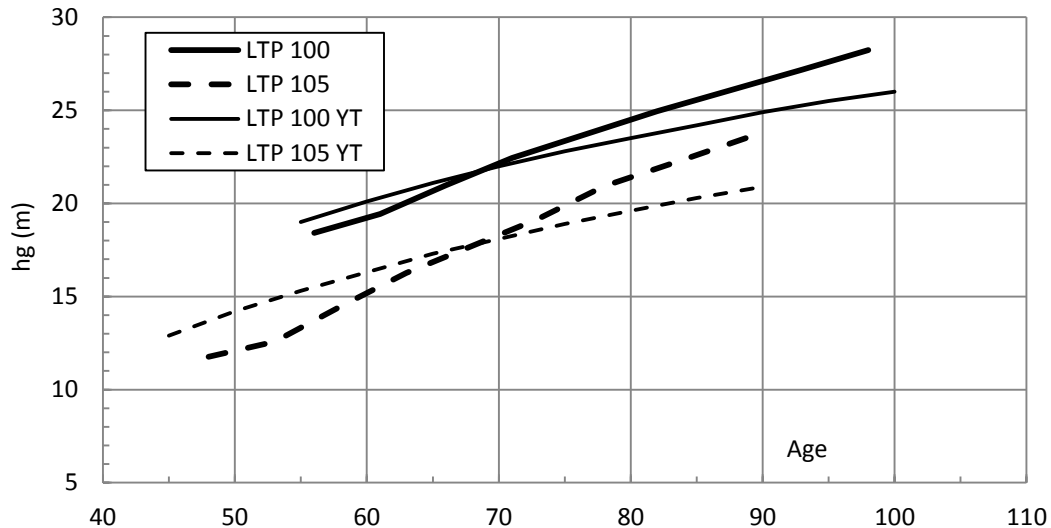


Figure 3. Comparison of mean height development hg on LTP 100 and 105 with the model one by yield tables (Halaj – Petráš 1998)

3.2 Changes in individual trees growth

Changes in tree growth were examined by tree ring series. Even when formation of tree rings is unambiguous in our climatic conditions, there are individual cases where tree rings vary. Two rings may form in some years, while no rings form or are scarcely recognizable in other years. Therefore, tree ring series were synchronized and dated to discover and eliminate these particularities. The percentage of parallelism in increment trends (Jačka 1989, Petráš et al. 1993) was calculated for all pairs of tree rings series apparent over the last 50 years. Results of this calculation delivered the wide range of 39–83%. Only 4 pairs of tree ring series exhibited less than 50% parallelism. Here, oaks with free crowns recorded the highest values up to 68–83%, while suppressed fir and beech ring series registered lower parallelism. This lower parallelism percentage confirmed that the tree ring series are correct.

In-depth analysis of tree ring series proceeded from our knowledge and experience. When growth conditions of examined trees change, the tree responds with changed increments. Thus, as conditions improve, both tree increments and variability increase, while their increments and variability are smaller in worsening conditions (Pollanschütz 1986, Petráš – Mecko 2011, Bošel'a et al. 2013, 2014). The timing of changes in growth conditions is also important. A sudden change in conditions induces radically larger or smaller increments in the increment curve. This knowledge was employed to investigate the actual influence of wild boars on radial increments in all 9 trees. The trees were divided into three groups for precise illustration. The first group comprised three oaks with long-term balanced increments and natural variability in the range of 1 to 4 mm (Figure 4). Despite considerable variability in increments, it was not possible to confirm marked depressions or increased increments in these trees during the 1965–2012 period. The second group included oak trees which experienced radial increments (Figure 5). The curves for trees number 2 and 4 indicate that more distinctive increment depressions occurred after 1980 or 1990, and they maintained this similar condition after the year 2000. From reasons stated above, we can conclude that neither depression was due to negative influences of wild boar activity near the trees, but rather was due to other causes. The most likely cause lies in the worsened position of the tree with respect to crown space. However, an exception to this is oak tree number 8 which grows on the lower side of the mud bath which has an approximate diameter of 4–5 m. This oak tree maintained its approximately balanced increments until 2005, and then a marked depression

occurred with increments decreasing from 1.3 mm to 0.4 mm. This was the minimum value recorded since 1930 in the entire study period. Since the crown of this tree is in the crown-level position, we can assume that this depression occurred because of the negative influence of the mud bath which is permanently filled with water and deep mud. In connection with this assumption, we stress the fact that oak tree number 9 (Figure 4), which has no increment depression, is located almost at the same distance from the mud bath, but on the upper aspect and thus negates a permanently wet root system. The third group consists of two firs and one beech tree (Figure 6). Fir tree number 5 is dominant; being the thickest of all trees. Since its increment variability is relatively broad, it is difficult to presume that the reason for its sudden increment depression over the last 3 years is due to wild boar activity. However, the situation with the beech tree is entirely different. This beech tree suffered distinct depression in 2005–2012, with following bigger increments between 1980 and 2004. Hence, the possibility certainly exists that negative influences emanated from wild boar activity.

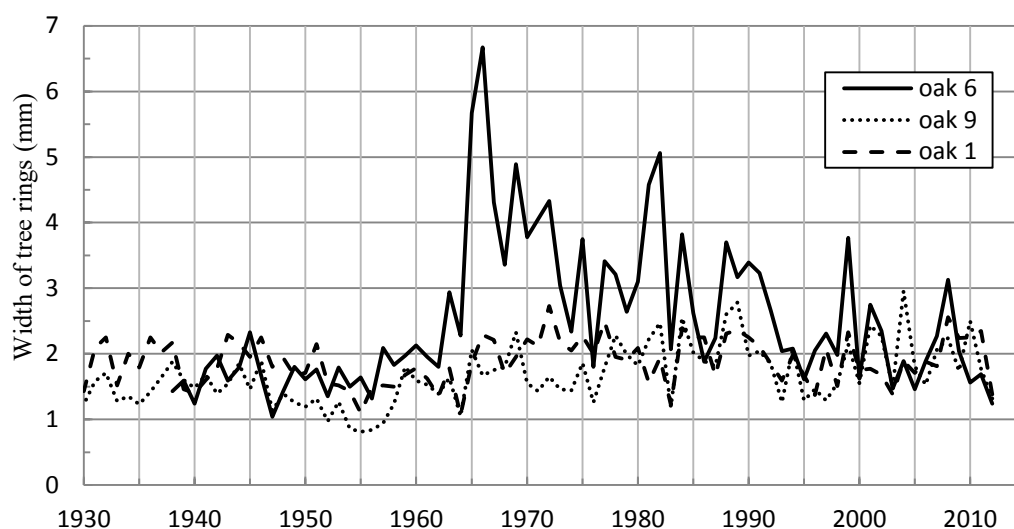


Figure 4. Radial increments of the oaks no. 1, 6 and 9 without any significant changes in the observed period

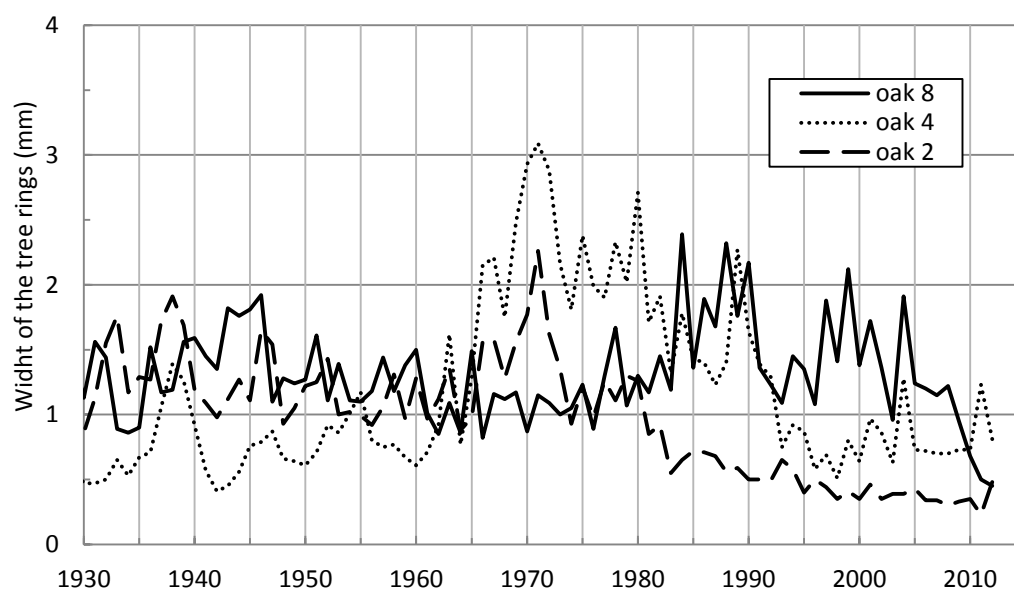


Figure 5. Radial increments of the oaks no. 2, 4 and 8 with more significant changes in the observed period

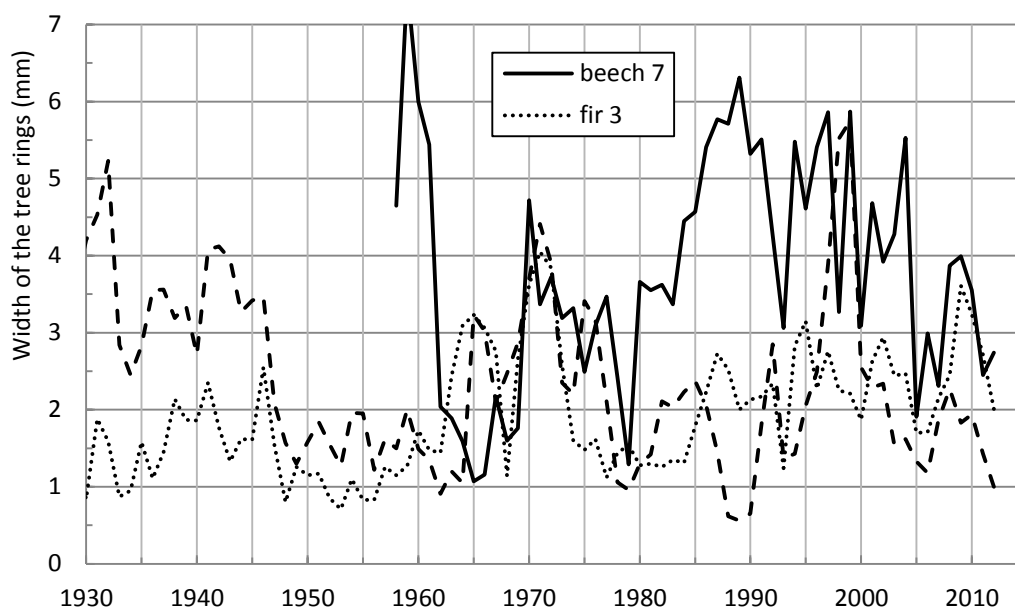


Figure 6. Radial increments of firs no. 3 and 5 and the beech with no. 7 with more significant changes in the observed period

On the basis of obtained results, we can state that soil surface rooting by wild boars cannot definitely be considered responsible for positive or negative influences. This certainly depends on scarification extent, depth, and intensity. In our two LTPs, there was whole-scale rooting, but only on the surface, with accompanying disruption of soil litter. The soil profile was not disturbed to a deep level in any area. In addition, although the approximate ten-year observation period of this study is relatively short, our intention is to continue monitoring these LTPs while the game preserve is maintained. This study has confirmed that analysis of radial increments on tree ring series is an appropriate and beneficial methodology designed for particular trees and their biotopes. Future research will enable increased precision in the study of these trees and their biotopes, and long-term monitoring of increased number of trees and tree species is pertinent.

4 CONCLUSION

The objective of this work was to investigate methods which will determine and quantify the impact of wild boars on the increment and growth of forest trees and stands. Their influence on hectare and mean stand variables was observed in a game preserve with intensive wild boar management. Long-term measurements obtained from two long-term research plots of sessile oak trees served as a basic material for this observation. Tree increments of more tree species were observed on tree ring cores coming from differently damaged soil surface surrounding those trees.

Results showed that shallow rooting of the soil surface caused by wild boars has no influence on oak stand growth. The development of mean heights and diameters on both the permanent sample plots observed over 41 years is continuous, without significant changes after the year 2000 when the game preserve for wild boars was established in this locality.

A significant influence of wild boars was proven only on radial increments in some individual trees. Deeper rooting of the soil surface had no effect on eight of the nine examined trees; these were six oak and two fir trees. However, the remaining beech tree proved an exception, exhibiting increment depression over the last seven years. Mud baths installed for

the wild boars in this game reserve had different effects on the surrounding trees. Radial increments on an oak growing on the lower side of the larger mud bath which was permanently filled with water and deeper mud decreased quite significantly after 2005.

Our results indicated that it is possible to expect negative influence on forest tree increment resulting from wild boars activity, and that this is only a question of extent and intensity. We can state that it cannot be considered as damage a priori. With respect to the small amount of empirical material available herein, it is necessary to consider the achieved results as preliminary results. The method based on observation of whole-stands growth changes on the basis of long-term measurements obtained from long-term research plots is not sufficiently sensitive to the whole-area rooting of the soil surface by wild boars. It is hard to assume whether it would be suitable for comparison of growth changes with a control variant, i.e. without any rooting. The method of observation of radial increments on tree ring cores is more sensitive and persuasive. It is based on the ability of individual trees to respond to changed growth conditions.

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Modelling of the 1D Convective Heat Exchange between Logs Subjected to Freezing and to Subsequent Defrosting and the Surrounding Environment

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Abstract – A 1D mathematical model for the computation of the temperature on the surface of cylindrical logs, t_{sr} , and the non-stationary temperature distribution along the radiuses of logs subjected to freezing and subsequent defrosting at convective exponentially changing boundary conditions has been suggested. The model includes mathematical descriptions of the thermal conductivity in radial direction, λ_r , the effective specific heat capacity, c_e , and the density, ρ , of the non-frozen and frozen wood, and also of the heat transfer coefficient between the surrounding air environment and the radial direction of horizontally situated logs, α_r . With the help of the model, computations have been carried out for the determination of α_r , t_{sr} , λ_{sr} , and 1D temperature distribution along the radiuses of beech logs with diameters of 0.24 m, initial temperature 20 °C, and moisture content 0.4 kg·kg⁻¹, 0.8 kg·kg⁻¹, and 1.2 kg·kg⁻¹, during their freezing at -20 °C, and during subsequent thawing at 20 °C.

heat transfer coefficient / surface temperature / temperature distribution / beech logs / radius

Kivonat – Egydimenziós konvektív hővezetés modellezése fagyott és normál állapotú rönk és környezte között. Célunk egy 1D matematikai modell létrehozása volt, amely kiszámítja a hengeres farönk felületi hőmérsékletét, t_{sr} , és a rönk sugara menti hőmérséklet-eloszlást egy olyan hengeres farönkön, amelyet lefagyasztottak majd kiolvasztottak exponenciálisan változó hőátadási körülmények között. A modell magában foglalja a sugárirányú hővezetési tényező, λ_r , az effektív specifikus fajhő c_e , és a sűrűség ρ matematikai leírását nem-fagyott és fagyott állapotú faanyag esetében. Tartalmazza továbbá az α_r radiális irányú hőátadási tényezőt a környező levegő és a vízszintesen fekvő rönk között. A modell segítségével számítások történtek az α_r , a t_{sr} , és a λ_{sr} , valamint az 1D hőmérsékleteloszlás meghatározására 0,24 m átmérőjű bükk rönknél a sugár mentén a következő feltételek mellett: kezdeti hőmérséklet 20 °C, a nedvességtartalom értékei 0,4 kg·kg⁻¹, 0,8 kg·kg⁻¹ és 1,2 kg·kg⁻¹, a -20 °C-os fagyasztás során és az ezt követő felolvasztás folyamán 20°C-ig.

hővezetési együttható / felületi hőmérséklet / hőmérsékleteloszlás / bükk rönk / sugár

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1 INTRODUCTION

Logs prepared for veneer production are subjected to freezing and thawing in natural air conditions during the winter. The duration time and energy needed for the thermal treatment of frozen logs with the goal of plasticizing depends greatly on the level of freezing within the logs. (Sergovsky 1975, Shubin 1990, Trebula – Klement 2002, Videlov 2003, Deliiski 2004, 2009).

In the accessible specialized literature there are very few reports about the temperature distribution in frozen logs subjected to thawing (Steinhagen 1986, 1991, Steinhagen et al. 1987, Steinhagen – Lee 1988, Khattabi – Steinhagen 1992, 1993, 1995, Deliiski 2005, 2011, 2013b) and there is no information at all about the temperature distribution in logs during their natural or artificial freezing. That is why the modelling and the multi-parameter study of the processes of freezing and of the subsequent defrosting (thawing) of logs are of considerable scientific and practical interest.

The aim of the present work is to suggest a 1D mathematical model for the computation of the temperature on the surfaces of cylindrical logs, t_{sr} , and the non-stationary temperature distribution along the radiuses of logs subjected to freezing and subsequent defrosting at convective exponentially changing boundary conditions. To achieve this goal, a base model of the heating and cooling processes of logs is used, one which has earlier been suggested and modified by the first co-author (Deliiski 2005, 2011, 2013b).

Symbols:

c	= specific heat capacity ($J \cdot kg^{-1} \cdot K^{-1}$)
D	= diameter, m
exp	= exponent
q	= specific heat energy ($kWh \cdot m^{-3}$)
r	= radial coordinate: $0 \leq r \leq R$, m;
R	= radius, m
t	= temperature ($^{\circ}C$): $t = T - 273.15$
T	= temperature (K): $T = t + 273.15$
u	= moisture content ($kg \cdot kg^{-1}$): $u = W/100$
W	= moisture content (%): $W = 100u$
α	= heat transfer coefficient between the logs' surface and the air environment ($W \cdot m^{-2} \cdot K^{-1}$)
Δ	= difference (for the temperature)
λ	= thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
ρ	= density ($kg \cdot m^{-3}$)
τ	= time (s)
@	= at

Subscripts and superscripts:

ad	= anatomical direction
b	= basic (for density, based on dry mass divided to green volume)
bw	= bound water
bwm	= maximum possible amount of bound water
c	= center (for the temperature or thermal conductivity on the logs' centers)
dfr	= defrosting (for the temperature of the defrosting medium)
e	= effective (for the specific heat capacity of the frozen and non-frozen wood)
exp	= exponent (for the time constant of the exponentially change in the air temperature)
fr	= freezing (for the temperature or for the duration of the freezing process or for the frozen state of the wood)

fsp	=	fiber saturation point of the wood
fw	=	free water
m	=	medium (for the temperature of the freezing or defrosting air environment)
m0	=	initial (for the medium temperature at the end of the logs freezing or defrosting)
m1	=	end (for the medium temperature at the end of the logs freezing or defrosting)
nfr	=	non-frozen (for the state of the wood)
r	=	radial direction
sr	=	surface on the radial direction
0	=	initial (for the radial or time coordinates or for the average mass temperature of the logs at the beginning of the freezing process)
1	=	final (for the average temperature of the logs at the end of the defrosting process)
273.15	=	at 273.15 K, i.e. at 0 °C (for the wood thermal conductivity)
293.15	=	at 293.15 K, i.e. at 20 °C (for the fiber saturation point of the wood)

2 MATERIAL AND METHODS

2.1 Mechanism of the 1D heat distribution in the logs

The mechanism of the heat distribution in logs during their heating or cooling can be described by the equation of heat conduction (also known as the equation of Fourier-Kirchhoff). When the length of the logs exceeds their diameter by at least 3 or 4 times, then the heat transfer through the frontal sides of the logs can be ignored, because it does not influence the change in temperature of their cross sections which are equally distant from the frontal sides (Chudinov 1968). In such cases, the following 1D model can be used for the calculation of the change in T only along the radius of the central cross sections during freezing and defrosting of the logs (i.e. along the coordinate r of these sections) (Deliiski 2011, 2013b):

$$c_e \rho \frac{\partial T(r, \tau)}{\partial \tau} = \lambda_r \left(\frac{\partial^2 T(r, \tau)}{\partial r^2} + \frac{1}{r} \frac{\partial T(r, \tau)}{\partial r} \right) + \frac{\partial \lambda_r(r, \tau)}{\partial T} \left(\frac{\partial T(r, \tau)}{\partial r} \right)^2 \quad (1)$$

with an initial condition

$$T(r, 0) = T_0 \quad (2)$$

and with one and the same boundary condition for the convective heat transfer valid for the entire surface of the logs:

- during the process of logs freezing:

$$\frac{\partial T(0, \tau)}{\partial r} = - \frac{\alpha_r^{\text{fr}}(\tau)}{\lambda_{\text{sr}}(\tau)} [T_{\text{sr}}^{\text{fr}}(\tau) - T_{\text{m}}^{\text{fr}}(\tau)], \quad (3)$$

- during the process of logs defrosting:

$$\frac{\partial T(0, \tau)}{\partial r} = \frac{\alpha_r^{\text{dfr}}(\tau)}{\lambda_{\text{sr}}(\tau)} [T_{\text{sr}}^{\text{dfr}}(\tau) - T_{\text{m}}^{\text{dfr}}(\tau)]. \quad (4)$$

It must be noted that the model presented by equations (1) ÷ (4) can also be solved with different mathematically described boundary conditions and heat transfer coefficients within them. The difference between the thermo-physical characteristics of the logs' bark and the logs' wood has not been taken into consideration in the model.

2.2 Change in the temperature of the freezing and the defrosting mediums

It is possible to have two cases for freezing of different materials in freezers. The first case is when the material is put into a working freezer with a constant unchanged temperature in it and, consequently, the freezing medium temperature $T_m(\tau) = T_{m0} = \text{const}$.

The mathematical model (1) ÷ (4) obtains more complicated boundary conditions in the second case; in this case the material is put into a freezer before it is switched on. Here, the temperature of the air environment in the freezer T_m^{fr} decreases exponentially (Figure 1) according to the equation

$$T_m^{\text{fr}} = T_{m1}^{\text{fr}} + (T_{m0}^{\text{fr}} - T_{m1}^{\text{fr}}) \exp\left(-\frac{\tau}{\tau_{\text{exp}}^{\text{fr}}}\right). \quad (5)$$

The defrosting of the frozen materials after the freezer's door is opened is realized at the exponential increase of the air temperature (Figure 1) according to the equation

$$T_m^{\text{dfr}} = T_{m1}^{\text{dfr}} - (T_{m1}^{\text{dfr}} - T_{m1}^{\text{fr}}) \exp\left(-\frac{\tau - \tau_{\text{fr}}}{\tau_{\text{exp}}^{\text{dfr}}}\right). \quad (6)$$

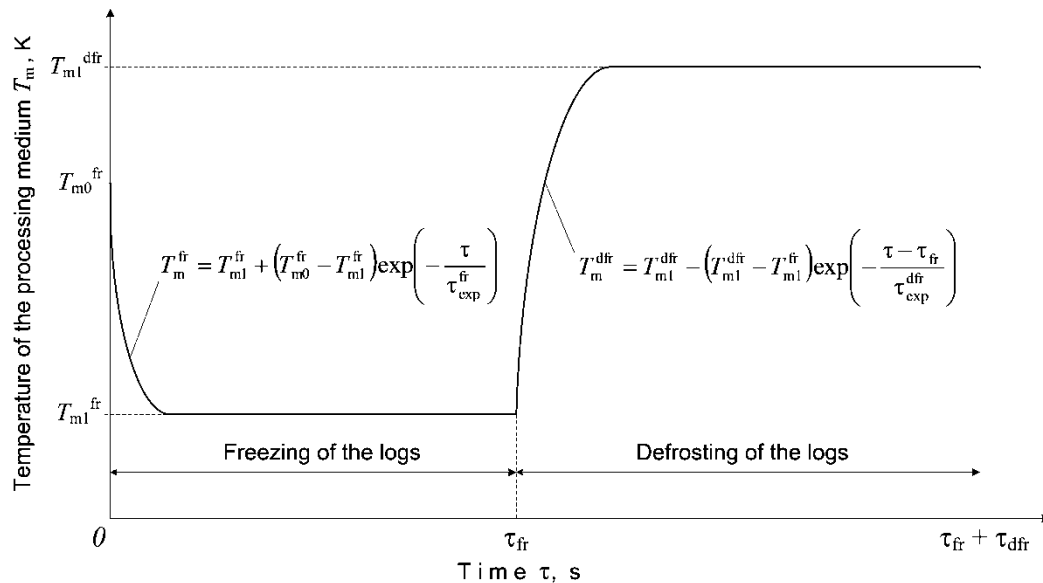


Figure 1. Exponential change in the air medium during the freezing and the defrosting of logs

2.3 Heat transfer coefficient between the air and the logs

It is known that the heating or cooling of logs in a gaseous (air) environment takes place through a convective heat exchange between the surfaces of the logs and the moving environment. If the movement is caused by differences in the density of the gas as a consequence of temperature differences in it, it is acceptable to call the convection free (not organized, natural).

As a rule, the freezing of wood materials at atmospheric conditions or in a freezer takes place in the conditions of free convection. For the calculation of the heat transfer coefficient in such conditions of heating or cooling of horizontally situated logs Chudinov (1968) suggests the following experimentally determined equation:

$$\alpha_r = 0.997 \sqrt[4]{\frac{\Delta T}{R}}. \quad (7)$$

It can be assumed that the heat transfer coefficients during freezing and defrosting of the materials are not equal to each other. Real free air convection is observed only during the freezing and defrosting of logs at natural atmospheric conditions or during the defrosting of frozen materials after the freezer's door is opened. That is why it can be written as:

$$\alpha_r^{\text{fr}} \approx 0.997 \sqrt[4]{\frac{\Delta T}{R}} = 0.997 \sqrt[4]{\frac{T(0, \tau) - T_m^{\text{fr}}(\tau)}{R}}, \quad (8)$$

$$\alpha_r^{\text{dfr}} = 0.997 \sqrt[4]{\frac{\Delta T}{R}} = 0.997 \sqrt[4]{\frac{T_m^{\text{dfr}}(\tau) - T(0, \tau)}{R}}. \quad (9)$$

More precise equations for the determination of the heat transfer coefficients between the surfaces of the logs in radial direction and the freezing or defrosting mediums can be obtained after suitable experiments have been carried out.

The model presented by equations (1) ÷ (4) can also be solved with different mathematically described heat transfer coefficients for separate parts of the logs' surfaces. The analysis and presentation of such cases are beyond the scope of this article.

2.4 Thermo-physical characteristics of the logs during their freezing and defrosting

The solution of the non-linear 1D mathematical model of the freezing and defrosting processes of logs, which is presented by the equations (1) ÷ (9), can be realized using the mathematical descriptions of the effective heat capacity of the frozen and non-frozen wood, c_e , the thermal conductivity of the wood in radial direction, λ_r , and the density of frozen and non-frozen wood, ρ , given in Deliiski (2011, 2013b). With the help of the mathematical description of λ_r , the current values of the thermal conductivity on the logs' surfaces in radial direction $\lambda_{sr}(0, \tau)$, which participates in eqs. (3) and (4), can also be calculated during the solution of the model.

The thermal conductivity of the wood can be calculated with the help of the following equations for $\lambda(T, u, \rho_b, u_{\text{fsp}})$:

$$\lambda = \lambda_{273.15} \gamma [1 + \beta(T - 273.15)], \quad (10)$$

$$\lambda_{273.15} = K_{\text{ad}} \nu [0.165 + (1.39 + 3.8u)(3.3 \cdot 10^{-7} \rho_b^2 + 1.015 \cdot 10^{-3} \rho_b)], \quad (11)$$

$$\nu = 0.15 - 0.07u \quad @ \quad u \leq u_{\text{fsp}} + 0.1 \text{ kg} \cdot \text{kg}^{-1}, \quad (12)$$

$$\nu = 0.1284 - 0.013u \quad @ \quad u > u_{\text{fsp}} + 0.1 \text{ kg} \cdot \text{kg}^{-1}. \quad (13)$$

Equations for the calculation of the variables γ and β in eq. (10) for frozen and non-frozen wood from different wood species and an algorithm for usage of the mathematical description of λ during the solution of the model are given in Deliiski (2013a).

The ice in the wood can be formed from the freezing of hygroscopically bound water or from both the bound and the free water in the wood. It is widely accepted that the phase transition of water into ice and vice versa can be expressed with the help of the so-called “latent heat” in the ice of the frozen body. When solving problems connected to transient heat conduction in frozen wood, it makes sense to include the latent heat in the so-called effective specific heat capacity c_e (Chudinov 1966, 1968), which is equal to the sum of the wood’s own specific heat capacity c and the specific heat capacity of the wood which is frozen only with bound water or contains both bound and free water within it. As an example, in *Figure 1*, the symbols of the thermo-physical characteristics of the frozen and non-frozen wood are present, which are necessary for the computation of the temperature distribution in the wood during heating aimed at its defrosting in the respective temperature diapasons and for the computation of the energy consumption for the heating of the wood.

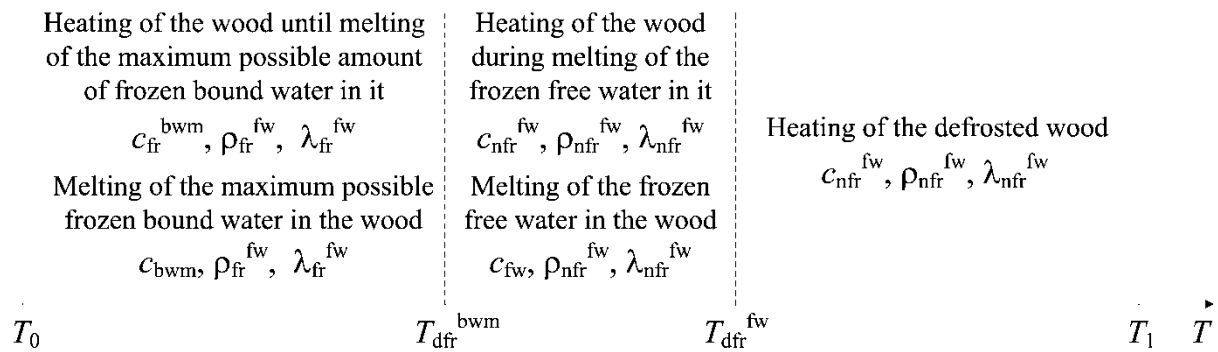


Figure 2. Using different specific heat capacities – c , thermal conductivities – λ and densities – ρ , for the calculation of the temperature distribution in frozen and non-frozen wood when $u > u_{fsp}$

A mathematical description of these characteristics is given in Deliiski (2013b). When modelling processes connected with non-stationary temperature distribution in frozen wood with $u > u_{fsp}$ during its defrosting, it is necessary to take into consideration that the effective specific heat capacity, c_e , for the separate temperature diapasons on *Figure 2* is equal to:

$$c_e = c_{fr}^{bwm} + c_{bwm} \quad @ \quad T_0 \leq T \leq T_{dfr}^{bwm}, \quad (14)$$

$$c_e = c_{nfr}^{fw} + c_{fw} \quad @ \quad T_{dfr}^{bwm} < T \leq T_{dfr}^{fw}, \quad (15)$$

$$c_e = c_{nfr}^{fw} \quad @ \quad T_{dfr}^{fw} < T \leq T_1. \quad (16)$$

During the computations of the freezing and defrosting processes of logs, effective heat capacities and densities of the wood subjected to thawing have been used and are shown in the mathematical descriptions of thermal conductivities below *Figure 2* (Deliiski 2011, 2013a, 2013b). The small difference (so named hysteresis) between these thermo-physical characteristics, and also between the temperatures T_{fr}^{bwm} and T_{dfr}^{bwm} , and between T_{fr}^{fw} and T_{dfr}^{fw} during the freezing and defrosting of the wood (Chudinov 1966, 1968) needs to be additionally studied and mathematically described.

3 RESULTS AND DISCUSSION

The abovementioned mathematical descriptions of T_m^{fr} , T_m^{dfr} , α_r^{fr} and α_r^{dfr} have been introduced before by the first co-author who earlier created and later modified a non-stationary model of the heating and cooling of cylindrical wood materials (Deliiski 2005, 2011, 2013b). This model is presented in common form by the eqs. (1) ÷ (4).

The updated model with the descriptions of T_m^{fr} , T_m^{dfr} , α_r^{fr} , and α_r^{dfr} has been solved with the help of explicit schemes of the finite difference method which, in a way, is analogous to the one used and described in (Deliiski 2009, 2011) for the solution of a model of the heating and cooling process of cylindrical wood materials. During the computations, these schemes allow for the determination of the temperature at each node of the calculation mesh using the current values of the thermo-physical characteristics of the frozen or non-frozen wood depending on the momentous aggregate state of the bound and free water in the wood in separate nodes.

To help with the solutions of the updated model, a software program has been prepared in the calculation environment of Visual FORTRAN Professional, which is a part of the office-package of Windows. The program helped carry out computations for the determination of the 1D change of temperature in beech logs (*Fagus Silvatica* L.) subjected to 50 hours freezing at $t_{m1}^{\text{fr}} = -20$ °C and a following 50 h defrosting at $t_{m2}^{\text{dfr}} = -20$ °C.

The freezing and subsequent defrosting of logs with a diameter of $D = 0.24$ m (i.e. with a radius of $R = 0.12$ m), initial wood temperature $t_0 = 20$ °C and three values of the wood moisture content: $u = 0.4$ kg·kg⁻¹, $u = 0.8$ kg·kg⁻¹, and $u = 1.2$ kg·kg⁻¹ have been studied. The moisture content of the beech logs is usually situated in this range of u , which are used for the production of veneer. All logs with such u contain a maximum possible quantity of bound water. Besides this, the logs with $u = 0.4$ kg·kg⁻¹ contain a relatively little amount of free water, the log with $u = 0.8$ kg·kg⁻¹ contains a significant quantity of free water and the log with $u = 1.2$ kg·kg⁻¹ contains almost a maximum possible quantity of free water.

The decreasing of t_m^{fr} from the value of $t_{m0}^{\text{fr}} = t_0 = 20$ °C to $t_{m1}^{\text{fr}} = -20$ °C = const and the following increasing of t_m^{dfr} from $t_{m1}^{\text{fr}} = -20$ °C = const to $t_{m1}^{\text{dfr}} = 20$ °C = const go exponentially with time constants $\tau_{\text{exp}}^{\text{fr}} = \tau_{\text{exp}}^{\text{dfr}} = 3600$ s. The calculated values according to eqs. (5) and (6) exponential change of t_m^{fr} and t_m^{dfr} can be seen in the Figure 2 for the curve of t_m .

The duration of 50 h of the logs freezing at $t_{m1}^{\text{fr}} = -20$ °C has been proven as being enough for the reaching of a complete freezing of the free water in the all of the studied logs. The calculations were done with average values of basic density of beech wood $\rho_b = 560$ kg·m⁻³ and fiber saturation point at 293.15 K (i.e. at 20 °C) of this wood $u_{\text{fsp}}^{293.15} = 0.31$ kg·kg⁻¹ (Nikolov – Videlov 1987, Pozgaj et al. 1997). A coefficient $K_r = K_{\text{ad}} = 1.35$ (Deliiski 2003, 2013a) in eq. (11) for the beech wood was used.

Table 1 shows the computed distribution of the temperature in 4 equally distant from each other nodes of the calculation mesh in the central cross-section of the beech log with $u = 0.8$ kg·kg⁻¹ at every 2 h of the freezing and of the following defrosting processes. The corresponding input data, which is used for the solution of the 1D model, is underlined in Table 1. The remaining input data, which is not underlined in this table, relates mainly to the

parameters of the equipment with which the thermal treatment of the wood materials with the aim of their freezing or defrosting is carried out. Using this input data, the energy parameters of the freezing or defrosting process and the efficiency from the usage of the equipment can be calculated. The fourth column from right to left on *Table 1* shows the calculated values of α_r according to eq. (8) and the last two columns of *Table 1* show the calculated values of the wood thermal conductivities on the log's surface, λ_{sr} , and in the center of the log, λ_c , during the freezing and defrosting processes.

In *Figure 3* the computed change in the freezing and in the defrosting medium temperatures, t_m^{fr} and t_m^{dfr} respectively (both temperatures are shown as t_m on the figure), in the surface temperature of the log, t_{sr}^{fr} and t_{sr}^{dfr} (both of them are shown as t_{sr} on the figure) and also in the temperature in the central points of the log, t_c , during the freezing and subsequent defrosting, depending on the wood moisture content, u , is shown.

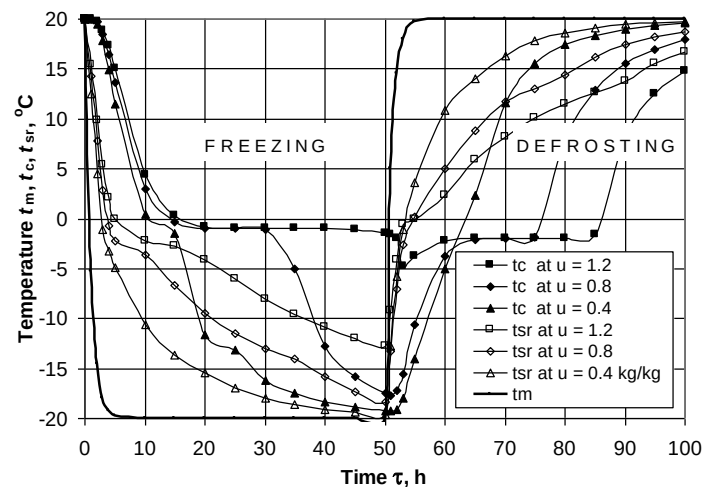


Figure 3. Change in t_m , t_{sr} , and t_c of beech logs with $D = 0.24$ m and $t_0 = 20$ °C during their 50 h freezing at -20 °C and following 50 h defrosting at 20 °C, depending on u

In *Figure 4* the computed change in the heat transfer coefficient between the surfaces of the logs in radial direction, α_r , and the freezing and defrosting mediums during the studied processes, depending on u is shown.

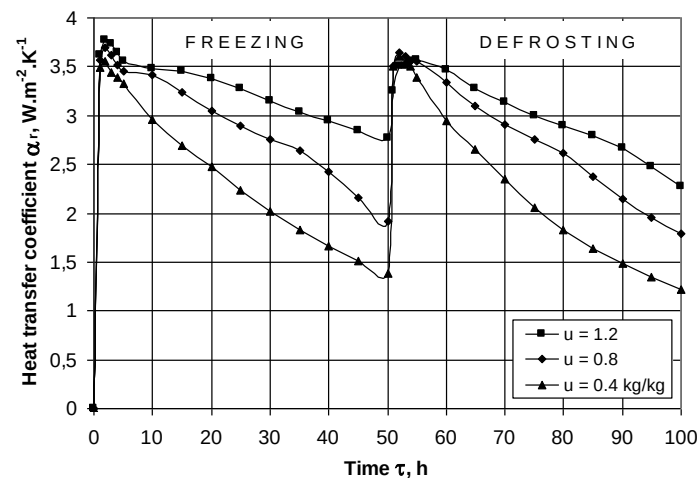


Figure 4. Change in α_r of beech logs with $D = 0.24$ m and $t_0 = 20$ °C during their 50 h freezing at -20 °C and following 50 h defrosting at 20 °C, depending on u

Table 1. Change in T_m^{fr} and T_m^{dfr} (third column), $T_{\text{sr}}^{\text{fr}}$ and $T_{\text{sr}}^{\text{dfr}}$ (fourth column), α_r (fourth column from right), in λ_{sr} and λ_c (second and first column from right), and in t in 4 equally distant from each other characteristic points of the central cross section of a beech log with $D = 0.24$ m, $t_0 = 20$ °C, and $u = 0.8$ kg·kg⁻¹ during every 2 h of its freezing at $t_{\text{ml}}^{\text{fr}} = -20$ °C and during the subsequent defrosting at $t_{\text{ml}}^{\text{dfr}} = 20$ °C

I N P U T D A T A													
FREEZING AND DEFROSTING OF A BEECH LOG WITH DIAMETER OF 0,24 m													
Kq=11 M= 11 N= 0 KD= 1 Ry=560. Kwr=1.35 Kwpr=1.78 U=0.800 Ufsp293=0.31 D=2.4 L= 9.0													
to= 20.0 tmo= 20.0 tmfr=-20.0 tmdfr= 20.0 t3= 0.0 t4= 0.0 dtm=.001 t01= 0. dTAU= 80													
Tfr=3600. Tdfr=3600. T3= 0. dT3= 0. dtm3= 0. T4= 0. T5= 0. TAUproc.=360000 INT= 7200													
ds=.008 Si=.10 Roi=120. Ai=.00000022 dFa=0.05 KK=.2 tcenter=-17.45 dtwc= 0.1 Ts= 0													
Pw=.30 Vw=14.39 Va=47.95 tbi= 0. Sim=0.200 Xp=1.00 L-log=0.00 D-log=.24 dx=.01200													
R E S U L T S													

Time	Energy	Temperature	Temp.in	charact.	points	on R,	tav	dtav/	ALFAr	LAMsr	LAMc		
TAU	q	tm	tsr	30	60	90	120	Simpson	Chud. Videl.	W/m2.K	W/m.K	W/m.K	W/m.K
h	kWh/m3	oC	oC	oC	oC	oC	oC	oC	oC/h				
0	0.00	20.0	20.00	20.0	20.0	20.0	20.0	20.00	0.00	0.00	0.00	0.534	0.534
2	3.28	-14.6	7.79	11.9	17.3	19.0	19.7	15.91	-3.18	3.69	4.36	0.514	0.533
4	8.49	-19.3	-0.76	3.0	10.4	14.1	16.4	9.37	-3.16	3.52	4.15	0.499	0.528
6	12.35	-19.9	-2.41	-0.1	4.9	8.4	10.8	4.75	-1.63	3.46	4.09	0.600	0.518
8	14.41	-20.0	-2.79	-0.9	2.2	4.4	6.1	2.14	-1.05	3.45	4.07	0.600	0.511
10	16.49	-20.0	-3.59	-1.1	0.7	2.0	3.0	0.49	-1.10	3.41	4.03	0.602	0.505
12	17.36	-20.0	-4.74	-1.8	-0.3	0.5	1.2	-0.67	-0.39	3.35	3.95	0.603	0.502
14	18.44	-20.0	-6.26	-3.8	-0.8	-0.3	0.1	-1.63	-0.37	3.26	3.85	0.606	0.501
16	19.75	-20.0	-7.14	-5.0	-1.0	-0.8	-0.6	-2.39	-0.52	3.21	3.79	0.607	0.499
18	20.14	-20.0	-8.41	-6.4	-1.1	-1.0	-0.9	-3.01	-0.19	3.13	3.69	0.609	0.499
20	21.00	-20.0	-9.50	-7.8	-1.7	-1.0	-1.0	-3.78	-0.27	3.05	3.60	0.610	0.499
22	22.27	-20.0	-10.33	-8.8	-3.7	-1.1	-1.0	-4.57	-0.37	2.99	3.53	0.612	0.499
24	23.03	-20.0	-11.14	-9.7	-4.6	-1.2	-1.0	-5.18	-0.73	2.92	3.45	0.613	0.499
26	23.49	-20.0	-11.87	-10.6	-6.2	-1.8	-1.0	-5.99	-0.28	2.86	3.38	0.614	0.499
28	24.78	-20.0	-12.44	-11.3	-7.3	-3.6	-1.0	-6.83	-0.37	2.81	3.32	0.615	0.499
30	25.12	-20.0	-13.00	-11.9	-8.1	-4.3	-1.1	-7.42	-0.24	2.76	3.25	0.616	0.499
32	26.01	-20.0	-13.47	-12.5	-9.1	-5.8	-1.2	-8.28	-0.31	2.71	3.20	0.616	0.498
34	27.30	-20.0	-13.89	-13.0	-9.8	-6.8	-1.7	-9.12	-0.48	2.66	3.15	0.617	0.498
36	28.52	-20.0	-14.32	-13.5	-11.0	-9.1	-7.5	-10.94	-1.01	2.62	3.09	0.617	0.607
38	29.46	-20.0	-15.03	-14.4	-12.7	-11.5	-10.6	-12.72	-0.79	2.53	2.99	0.619	0.612
40	30.19	-20.0	-15.82	-15.3	-14.1	-13.2	-12.7	-14.12	-0.62	2.42	2.86	0.620	0.615
42	30.76	-20.0	-16.53	-16.1	-15.2	-14.6	-14.1	-15.24	-0.49	2.31	2.73	0.621	0.617
44	31.21	-20.0	-17.12	-16.8	-16.1	-15.6	-15.3	-16.12	-0.40	2.21	2.61	0.622	0.619
46	31.56	-20.0	-17.61	-17.4	-16.8	-16.4	-16.2	-16.83	-0.32	2.11	2.49	0.622	0.620
48	31.85	-20.0	-18.01	-17.8	-17.4	-17.1	-16.9	-17.40	-0.25	2.01	2.38	0.623	0.621
50	32.08	-20.0	-18.34	-18.2	-17.8	-17.6	-17.5	-17.85	-0.20	1.92	2.27	0.623	0.622
52	30.00	14.5	-7.07	-10.3	-14.9	-16.5	-17.2	-13.80	3.22	3.65	4.32	0.607	0.622
54	25.73	19.3	-0.15	-3.1	-8.4	-11.3	-13.1	-7.79	2.05	3.56	4.20	0.500	0.616
56	23.67	19.9	0.48	-2.0	-5.0	-7.0	-8.5	-4.81	1.04	3.56	4.20	0.501	0.609
58	21.64	20.0	2.78	-1.3	-3.3	-4.6	-5.5	-2.84	0.65	3.45	4.07	0.505	0.605
60	20.23	20.0	4.96	1.6	-2.4	-3.2	-3.8	-1.36	0.55	3.34	3.94	0.509	0.602
62	18.49	20.0	6.61	3.9	-2.0	-2.4	-2.8	-0.05	0.54	3.24	3.83	0.511	0.600
64	17.27	20.0	8.01	5.7	-1.6	-2.1	-2.2	1.03	0.55	3.15	3.72	0.514	0.600
66	15.64	20.0	9.27	7.2	0.8	-2.0	-2.0	2.10	0.69	3.07	3.62	0.516	0.599
68	13.56	20.0	10.41	8.6	2.1	-1.8	-2.0	2.96	1.08	2.98	3.52	0.518	0.497
70	12.71	20.0	11.32	9.7	4.2	-1.2	-2.0	4.05	0.37	2.91	3.43	0.519	0.497
72	11.81	20.0	12.06	10.6	5.8	1.3	-2.0	5.18	0.42	2.84	3.36	0.520	0.497
74	11.03	20.0	12.71	11.4	7.0	2.9	-1.9	6.18	0.54	2.78	3.29	0.522	0.497
76	10.36	20.0	13.28	12.1	8.0	4.0	-1.6	7.03	1.61	2.73	3.22	0.522	0.498
78	8.89	20.0	13.76	12.7	9.1	6.2	3.7	8.89	1.24	2.68	3.16	0.523	0.506
80	7.21	20.0	14.38	13.5	11.0	9.2	7.9	11.01	0.91	2.61	3.08	0.524	0.514
82	5.93	20.0	15.14	14.4	12.5	11.3	10.4	12.62	0.71	2.52	2.97	0.526	0.518
84	4.92	20.0	15.86	15.3	13.8	12.9	12.2	13.88	0.56	2.42	2.85	0.527	0.521
86	4.11	20.0	16.47	16.0	14.8	14.1	13.6	14.89	0.46	2.32	2.74	0.528	0.523
88	3.46	20.0	16.99	16.6	15.7	15.1	14.6	15.71	0.37	2.23	2.64	0.529	0.525
90	2.92	20.0	17.42	17.1	16.3	15.8	15.5	16.38	0.30	2.15	2.54	0.529	0.526
92	2.48	20.0	17.78	17.5	16.9	16.5	16.2	16.93	0.25	2.07	2.44	0.530	0.527
94	2.11	20.0	18.09	17.9	17.3	17.0	16.8	17.38	0.21	1.99	2.35	0.530	0.528
96	1.81	20.0	18.34	18.2	17.7	17.5	17.3	17.76	0.17	1.92	2.27	0.531	0.529
98	1.56	20.0	18.56	18.4	18.0	17.8	17.7	18.07	0.14	1.86	2.19	0.531	0.530
100	1.35	20.0	18.74	18.6	18.3	18.1	18.0	18.34	0.12	1.79	2.12	0.532	0.530

E N D													

The computed change in the thermal conductivity of the surfaces of the logs in radial direction, λ_{sr} , and of the centres of the logs λ_c , depending on u during the freezing and defrosting processes is shown in Figure 5.

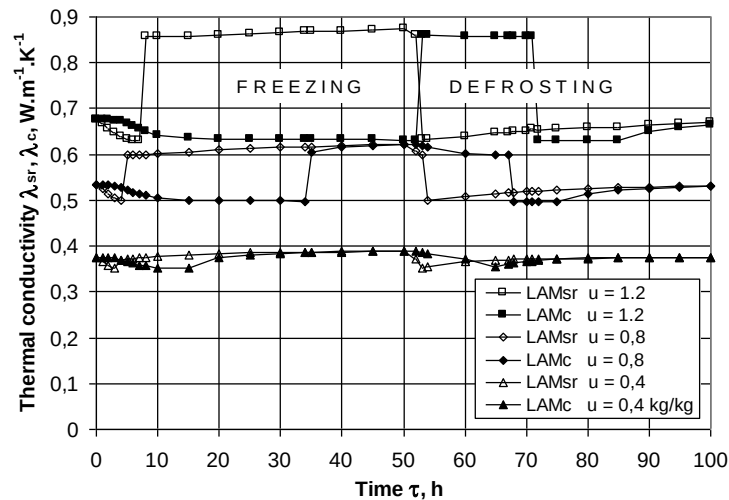


Figure 5. Change in λ_{sr} and in λ_c of beech logs with $D = 0.24$ m and $t_0 = 20$ °C during their 50 h freezing at -20 °C and following 50 h defrosting at 20 °C, depending on u

In Deliiski (2009) curves showing the percentage of water being in ice-phase on the diameter of beech logs subjected to defrosting with $t_0 = -20$ °C as a function of $u > u_{fsp}$ and the relationship τ / D can be seen.

The obtained results lead to the following conclusions:

1. On the curves of characteristic points situated on the logs' centers in Figure 3. the specific almost horizontal sections of retention of the temperature t_c for a long period of time in the range from -1 °C to -2 °C can be seen, while in these points a complete freezing of the free water and after that a complete melting of the ice created by it occurs in the wood (Chudinov 1966, 1968).

It can be noted that such retention of the temperature on the logs' axes has been observed in wide experimental studies during the defrosting process of pine logs containing ice from the free water (Steinhagen 1986, Khattabi – Steinhagen 1992, 1993).

2. The character of the change in the heat transfer coefficient, α_r , is almost identical during the studied freezing and defrosting processes of logs with given value of the wood moisture content (Figure 4). The reason for this is the equality of the difference $t_0 - t_m^{fr}$ during the freezing with the difference $t_m^{dfr} - t_{m1}^{fr}$ during the defrosting for one and the same moments from the beginning of these processes at $t_{m0}^{fr} = 20$ °C, $t_{m1}^{fr} = -20$ °C, $t_{m1}^{dfr} = 20$ °C, and $\tau_{exp}^{fr} = \tau_{exp}^{dfr} = 3600$ s. At other values of these variables, the change in α_r during the freezing and the defrosting would be different.

3. With the increase of the duration of the freezing and the defrosting processes, the coefficient α_r decreases because of the decreasing of the difference ΔT between the processing medium temperature and the surface temperature of the logs (see eqs. (8) and (9)).

4. The character of the change in the wood thermal conductivity on the logs' surfaces, λ_{sr} , and in the logs' centers, λ_c , is very complex (Figure 5). The current values of λ_{sr} and of λ_c depend not only on the wood moisture content and on the current temperature in the respective points on the logs' radiuses, but also on the momentous aggregate condition of the water in these points (Deliiski, 2013a). The larger values of λ_{sr} and λ_c in Figure 5 related to

the central points or surfaces of the frozen logs, and the lower values of λ_{sr} and λ_c related to the logs' points with frozen free water in them at respective moments.

Table 1, Figure 3, and Figure 5 show that the complete freezing of the free water at the surface and at the center of the beech log with $u = 0.8 \text{ kg} \cdot \text{kg}^{-1}$ occurs between 4 and 6 h and between 34 and 36 h respectively, when the temperature in these points becomes lower than -2°C . Analogously, the melting of the frozen free water at the surface and at the center of this log starts between 52 and 54 h and between 66 and 68 h respectively. The complete melting of the frozen free water at the center of the log occurs between 76 and 78 h, when the temperature in this point becomes higher than -1°C .

4 CONCLUSIONS

The present paper describes the 1D mathematical model for the computation of the temperature on the surfaces of logs suggested by the authors, t_{sr} , and the non-stationary temperature distribution along the radiuses of logs subjected to freezing and to subsequent defrosting at convective exponentially changing boundary conditions. As a base model, the heating and cooling processes of logs is used, which was created and modified earlier by the first co-author. The mechanism of the heat distribution along the radiuses of the logs during their freezing and subsequent defrosting is described by the 1D partial differential equation of heat conduction. For the solution of the model, an explicit form of the finite-difference method is used, which allows for the exclusion of any simplifications in the model.

For the numerical solution of the model, a software program has been prepared in FORTRAN, which has been input in the Visual Fortran Professional calculation environment developed by Microsoft. With the help of the program an example computation has been carried out for the determination of the 1D change in the temperature along the radiuses of beech logs with diameter 0.24 m, initial temperature 20°C and moisture content $0.4 \text{ kg} \cdot \text{kg}^{-1}$, $0.8 \text{ kg} \cdot \text{kg}^{-1}$ and $1.2 \text{ kg} \cdot \text{kg}^{-1}$, during 50 hours freezing at exponentially decreasing air temperature until reaching of -20°C and during the following 50 h defrosting at exponentially increasing air temperature until reaching of 20°C .

The results presented in the figures in this paper show that the procedures for calculation of the non-stationary 1D temperature change in the prepared software program function well for the mutually connected processes of the freezing and the defrosting of the logs at convective boundary conditions.

The obtained results show the complex character of the change in the temperature on the logs' surfaces and along the logs' radiuses, and also of the heat transfer coefficient between the logs' surfaces and the processing freezing or defrosting air environment. Also the change in the wood thermal conductivity on the logs' surfaces and in the separate points along the logs' radiuses, especially strong depending on the aggregate condition of the water in each point at every moment of the studied processes, has a very complex character.

The presented model, after its update with new experimentally obtained data about the heat transfer coefficient and with mathematically described hysteresis between the thermo-physical characteristics of the wood during its freezing and defrosting, can be used for a science-based determination of the duration of the freezing and defrosting processes of logs at different initial and boundary conditions.

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